MAY 15 1926

Volume XXI April, 1926 Number 4

SOIL SCIENCE

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PUBLISHED MONTHLY
THE WILLIAMS & WILKINS COMPANY
MT. ROYAL AND GUILFORD AVENUES
BALTIMORE, MARYLAND, U.S.A.

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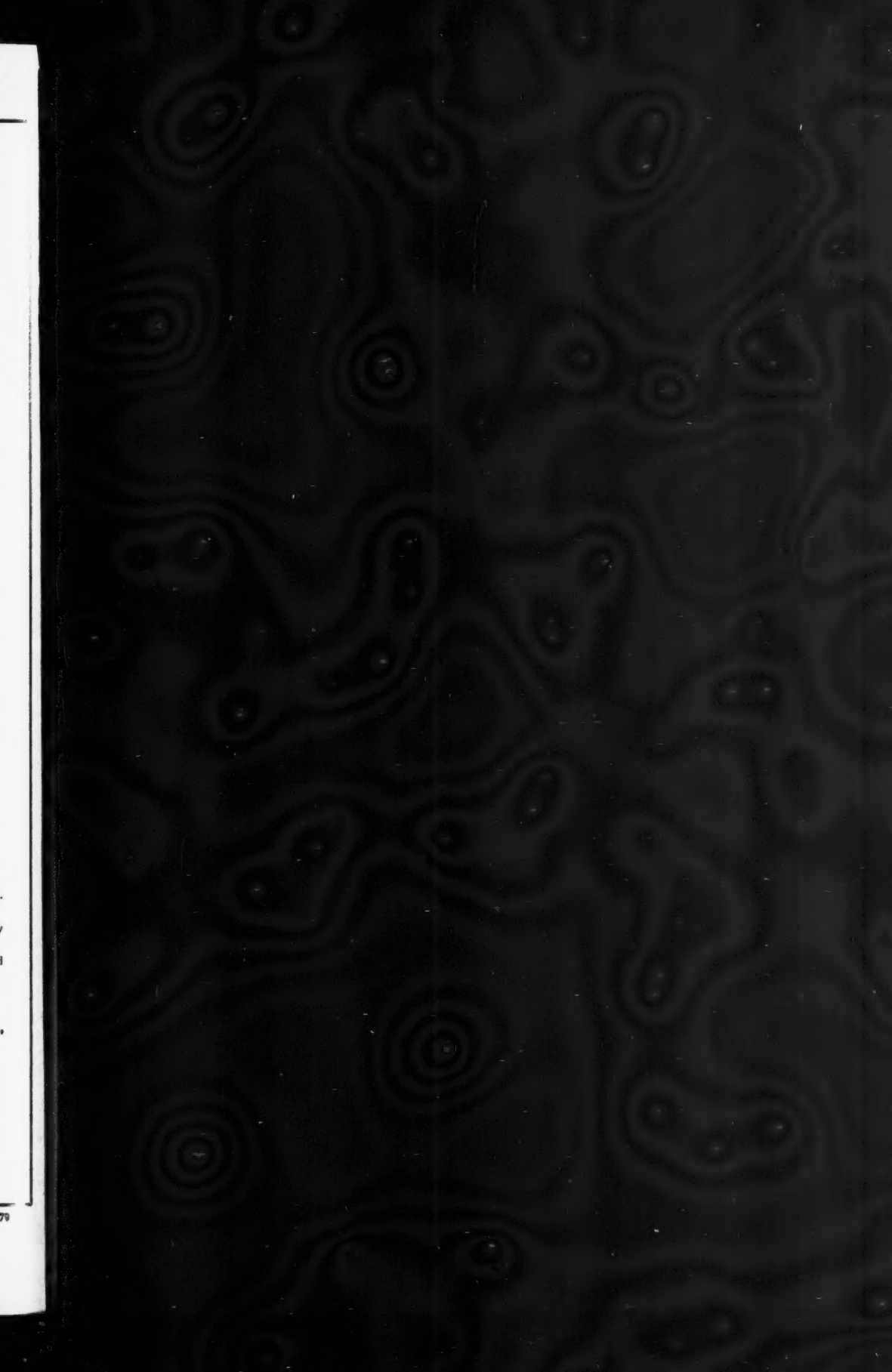

THE EFFECT OF SULFUR ON THE MICROFLORA OF THE SOIL

J. M. FIFE[1]

Utah Agricultural Experiment Station

Received for publication August 25, 1925

Sulfur is a vital part of the protein molecule, hence it is required by all plants and animals. All bacteria require it as a structural element and some use it as a source of energy. The quantity present in the soil of our Greenville experimental farm is low, 0.0068 per cent total sulfur (7) in the first foot. This being the case, the question naturally arises: What effect will the addition of sulfur to such a soil have upon its microflora? The data presented in this paper are an attempt to answer this question.

The Greenville soil is an ideal medium in which to make such a study, as it has an abundance of all the essential elements except sulfur and nitrogen, and it has a most interesting microflora (6, 7).

Boullanger (3) studied the action of sulfur on sterilized and unsterilized soil and found the increase in crop yield, due to the sulfur, was much greater on unsterilized soil. This action he considered to be due to the oxidation of sulfur by bacteria. This is confirmed by Demolon (5) with garden soil. The sulfofying power of soils varies with the composition, texture, moisture, and biological conditions (4). Lipman and co-workers (12) studied the oxidation of sulfur and its relations to insoluble plant-food. Sulfur is oxidized by certain bacteria to sulfuric acid as follows (10): $2S + 3O_2 + 2H_2O = 2H_2SO_4$. The acid reacts with insoluble phosphates rendering them soluble: $Ca_3(PO_4)_2 + H_2SO_4 + 2H_2O = Ca_2H_2(PO_4)_2 + CaSO_4 \cdot 2H_2O$.

$$Ca_2H_2(PO_4)_2 + H_2SO_4 = CaH_4(PO_4)_2 + CaSO_4$$

Many tests have been made to determine the effect of added sulfur on crop production. Reimer and Tartar (16) increased the yield of alfalfa and clover from 35 to 1000 per cent by the addition of sulfur to certain Oregon soils. The addition of sulfur to the soil increased the nitrogen content of plants and also the nodule production (13, 17). Rudolfs (17) using soybeans found that small amounts of sulfur increased the growth of the root systems. He also found that sulfur increased bacterial numbers during the first 6 weeks, when the sulfur application did not exceed 1500 pounds per acre. Greater quantities caused a decrease in numbers. This was confirmed by O'Gara (14).

[1] The author is greatly indebted to Dr. J. E. Greaves for his keen interest in this work and for his advice and suggestions, and to Dudley Greaves for making the graphs.

Small amounts of sulfur increase ammonification (1,15), whereas nitrification is retarded (1, 15). Sulfur oxidation is greater in soils low in organic matter and in mineral nutrients (17). One experiment shows that sulfur oxidation was greatest in soil which had no fertilizer for 33 years.

The addition of sulfur to black alkali soil in the presence of sulfur-oxidizing bacteria transforms the black alkali into white alkali (8, 14, 18, 21), thus indicating the possibility of its use in reclamation of alkali land.

The most important sulfur bacteria found in soils to which sulfur has been added are *Thiobacillus thioparus*, *Thiobacillus dentrificans* and *Thiobacillus thiooxidans* (19). The first two organisms develop under neutral or slightly alkaline conditions whereas the latter develops in extremely acid media reactions. Starkey (19) states that *Thiobacillus thiooxidans* not only tolerates but produces higher concentrations of acid than any other living organism.

In this work a laboratory study was made of the influence of varying amounts of sulfur on the soil microflora as measured by numbers, ammonification, nitrification, azofication, and the rate at which the sulfur is oxidized to sulfates.

Three soils were used, two of which were taken from the Greenville experimental farm located 2 miles north of the Utah Agricultural College. Soil A was taken from a plot which was very low in organic matter (this plot had received no manure for 12 years). Soil B was taken from a nearby plot which was very high in organic matter (40 tons of manure per acre had been applied yearly for 12 years). These soils are very high in calcium and magnesium carbonates (9) and exceptionally rich in potassium and phosphorus, but they are low in nitrogen. They are composed primarily of coarse and medium silt and fine sand. Soil C was taken from a farm in River Heights, 2 miles southwest of the college. This soil has a medium organic content and consists principally of coarse silt and medium sand. It is high in calcium and magnesium carbonates with ample amounts of phosphorus and potassium present, but low in nitrogen.

The three soils used were air-dried in the dark and were ground to pass a 40-mesh sieve, after which 100-gram portions were weighed into clean covered tumblers, to each of which were added quantities of sulfur varying from 100 to 1000 pounds per acre. One acre-foot of soil was assumed to weigh 3,600,000 pounds. The ammonifiers and nitrifiers, received in addition to the sulfur, 2 per cent dried blood containing 0.0272 per cent nitrogen (6). The nitrogen fixers received the same sulfur application and 2 per cent mannite. Each sample was thoroughly mixed and the water content made up to 60 per cent of the water-holding capacity. It was kept close to this amount by weekly weighings and the loss was made up with distilled water.

Four sets of each soil were prepared in the foregoing manner and incubated at 28°. After 4 days one set of each soil was analyzed for ammonia by the standard magnesium-oxide method (2). The bacterial counts were made at monthly intervals by the plate method using nutrient agar with a + 0.1 per cent reaction.

To determine sulfur oxidation 15 samples of each soil were prepared: to 9 of each soil was added 21.6 mgm. of sulfur; the remaining 6 received no sulfur and served as controls. The samples were thoroughly mixed and the moisture content made up to 60 per cent of the water-holding capacity, which was kept close to this percentage by weekly additions of distilled water. The three soils were incubated at 28° and the soluble sulfate was determined in three

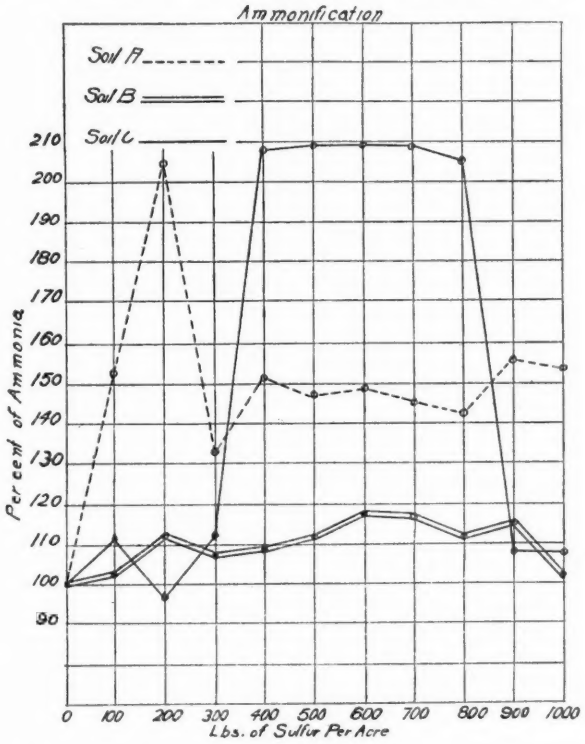

FIG. 1. PERCENTAGE OF AMMONIA PRODUCED IN SOILS TREATED WITH VARYING AMOUNTS OF SULFUR

The untreated soil was considered as 100 per cent

sulfur-treated samples and two untreated samples of each soil at intervals of 10 days. The sulfates were determined by agitating the soil with distilled water in a shaker for 5 hours, filtering clear, and precipitating as barium sulfate.

The results obtained for ammonification are given in figure 1. It is very evident that sulfur greatly stimulates ammonification in all three soils. Soil A showed greatest stimulation at the lower concentrations of sulfur. Sulfur

increased ammonification 100 per cent when small concentrations were used and 50 per cent with large concentrations.

The stimulation was not so great in soil B as in soils A and C. This is probably due to the large amounts of available plant-food already present in the soil which has been carried there by the heavy applications of manure. Ammonification was increased most in soil C; although sulfur appeared to be

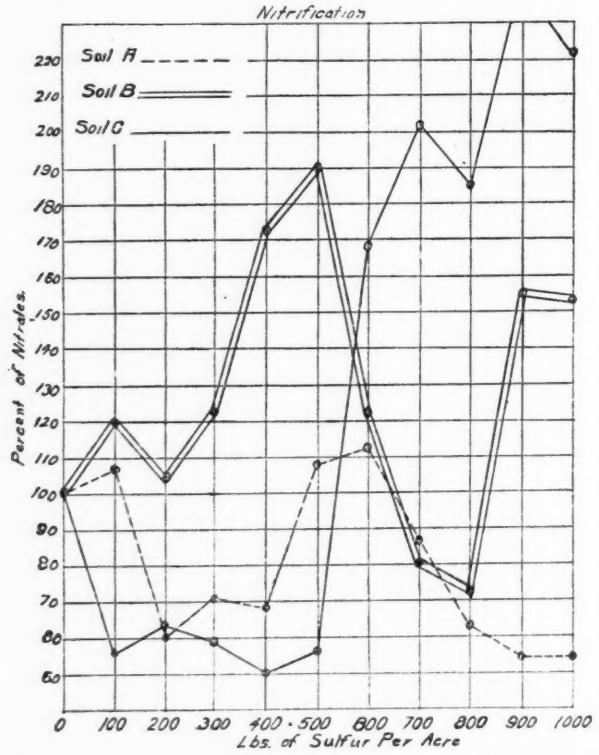

FIG. 2. PERCENTAGE OF NITRATES PRODUCED IN SOILS TREATED WITH VARYING AMOUNTS OF SULFUR

The untreated soil was considered as 100 per cent

slightly toxic in the second concentration, recovery was very marked in higher concentrations. When 400 pounds per acre of sulfur was applied to the soil, ammonification was increased 110 per cent. The probable cause of the great stimulation may be due to two factors:

(*a*) There may be a very small amount of available food present in the soil; consequently, the food made available by the oxidation of the sulfur would be quickly utilized, thus increasing the number of bacteria as well as their physiological efficiency. (*b*) The soil is in ideal

condition for the rapid oxidation of the sulfur, as it is loose and porous, thus admitting large amounts of oxygen and carbon dioxide which are necessary for the optimum activity of the sulfur organisms.

The nitrifying organisms responded to sulfur applications very differently from the ammonifying organisms. The sulfur was very toxic in soil A, the highest concentrations of sulfur appearing to be slightly more toxic than the lower concentrations. Nitrification was greatly stimulated in soil B by sulfur in all the concentrations with the exception of the seventh and eighth. At these two the sulfur became toxic. Although the sulfur was very toxic at all the lower concentrations, in soil C, a great stimulation occurred in the higher concentrations. In explanation of the broken line in soil C (fig. 2) it may be

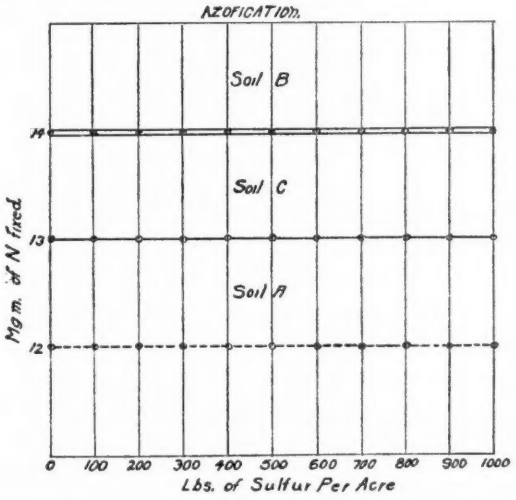

FIG. 3. MILLIGRAMS OF NITROGEN FIXED IN SOILS TREATED WITH VARYING AMOUNTS OF SULFUR

stated that an erratic result was obtained in the ninth concentration which threw the percentage of nitrates formed to 300 per cent above the untreated soil. It is very evident that the organic matter is playing a great part in the stimulation of nitrate production. The only difference in soils A and B is that soil B contains large amounts of organic matter, whereas soil A contains none.

The sulfur was without effect on azofication during the short time the soil was under observation, as may be seen from figure 3.

The number of colonies developing on nutrient agar from sulfur-treated and non-sulfur-treated soil is shown in figure 4.

There is a general decrease in the number of bacteria over the period the counts were made in the treated and in the untreated soils. Soils A and C

show a very slight increase in bacterial numbers when 5.4 mgm. of sulfur was present for each 100 gm. of soil, in comparison with the untreated soil. An increase in bacterial numbers was noted in soil B at the higher concentrations of sulfur.

If the bacterial numbers had been determined at weekly intervals during the time of incubation, it is very probable that a considerable increase due to the sulfur would have been noted.

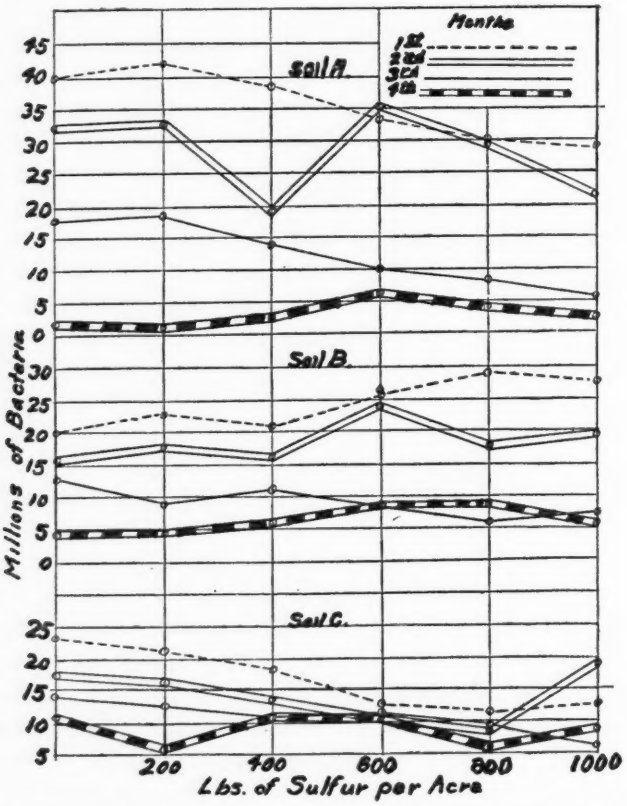

FIG. 4. MILLIONS OF BACTERIA IN SOILS TREATED WITH VARYING AMOUNTS OF SULFUR

The speed with which the sulfur is oxidized to sulfates is governed largely by the aeration of the soil. The physical composition of soil C makes conditions ideal for the free circulation of air. This is the chief cause of the very rapid oxidation of sulfur in this soil. In comparing the sulfur-oxidizing power of soils A and B, which vary only in organic content, a considerable difference

is noted in the amount of sulfur oxidized. Soil A, which was very low in organic matter, oxidized 36 per cent of the added sulfur in 30 days, whereas soil B, which contained large amounts of organic matter, oxidized 45 per cent of the added sulfur in the same period of time.

The addition of sulfur to soil increased the ammonifying power of the soil from 50 to over 100 per cent depending upon the soil and upon the amount of sulfur applied.

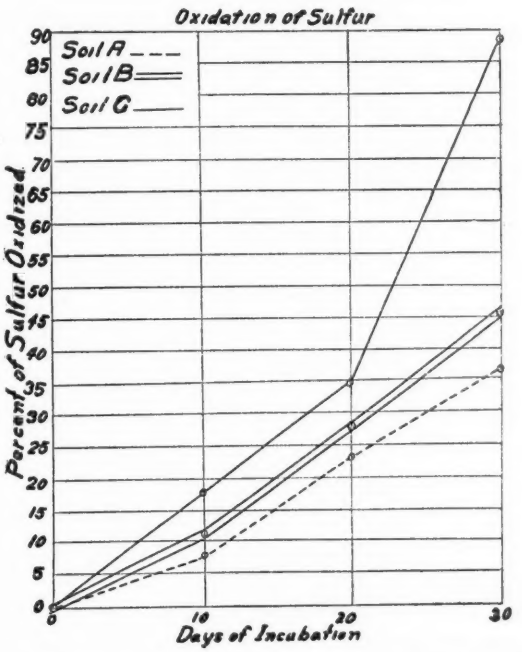

FIG. 5. PERCENTAGE OF SULFUR OXIDIZED IN SOILS TREATED WITH SULFUR
The untreated soil was considered as 100 per cent

Nitrification was increased over 100 per cent in some instances, the extent depending upon the soil and upon the quantity of sulfur added.

Sulfur was without effect on the azofication of the soil during the short period it was under observation.

The bacterial counts decreased as the incubation period increased. Relative to the untreated soil, the bacterial numbers increased as the amount of sulfur increased, in the soil high in organic matter; whereas the bacterial number of soils low in organic matter decreased as the sulfur increased.

From 36 to 89 per cent of the sulfur was oxidized to sulfates in 30 days, depending on the soil and its porosity.

REFERENCES

(1) Ames, J. W., and Richmond, T. E. 1918 Sulfofication in relation to nitrogen transformations. *In* Soil Sci., v. 5, p. 311–321.

(2) Association of Official Agricultural Chemists 1920 Official and tentative methods of Analysis. Assoc. Off. Agr. Chem., Washington, D. C.

(3) Boullanger, E. 1912 The action of sulfur on plants. *In* Compt. Rend. Acad. Sci. (Paris), v. 154, p. 369–370. *Abs. in* Exp. Sta. Rec., v. 27, p. 27.

(4) Brown, P. E., and Kellogg, E. H. 1914 Sulfofication in soils. *In* Iowa Agr. Exp. Sta. Res. Bul. 18, p. 49–111.

(5) Demolon, A. 1913 Investigations on the fertilizing action of sulfur. *In* Compt. Rend. Acad. Sci. (Paris), v. 156, p. 725–728. *Abs. in* Exp. Sta. Rec., v. 29, p. 25.

(6) Greaves, J. E., and Nelson, D. H. 1923 The influence of nitrogen in soil on Azofication. Utah Agr. Exp. Sta. Bul. 185.

(7) Greaves, J. E., and Nelson, D. H. 1924 The iron, chlorine, and sulfur contents of grains and the influence of irrigation water upon them. *In* Soil Sci., v. 19, p. 325–330.

(8) Hibbard, P. L. 1921 Sulfur for neutralizing alkali soil. *In* Soil Sci., v. 11, p. 385–387.

(9) Hirst, C. T., and Greaves, J. E. 1925 The influence of manure and irrigation water on the carbon, phosphorus, calcium and magnesium of the soil. *In* Soil Sci., v. 19, p. 87–97.

(10) Joffe, Jacob S. 1921 Studies of sulfur oxidation in sulfur-floats-soil mixtures. *In* Soil Sci., v. 13, p. 107–118.

(11) Joffe, J. S. and McLean, H. C. 1921. A note on oxidation of sulfur in Oregon soils. *In* Soil Sci. v. 14, p. 217–221.

(12) Lipman, Jacob G., Waksman, Selman A., and Joffe, Jacob S. 1921 The oxidation of sulfur by soil microörganisms. *In* Soil Sci., v. 12, p. 475–489.

(13) Miller, H. G. 1919 Relation of sulfates to plant growth and composition. *In* Jour. Agr. Res., v. 17, p. 87–102.

(14) O'Gara, P. J. 1917 Available fertilizer from smelter by-products. *In* Wash. Irrig. Inst. Proc., v. 5, p. 102–110. *Abs. in* Exp. Sta. Rec., v. 41, p. 427.

(15) Pitz, Walter 1916 Effect of elemental sulfur and of calcium sulfate on certain of the higher and lower forms of plant life. *In* Jour. Agr. Res., v. 5, p. 771–780.

(16) Reimer, F. C., and Tartar, H. V. 1919 Sulfur as a fertilizer for alfalfa in southern Oregon. Ore. Agr. Exp. Sta. Bul. 163.

(17) Rudolfs, W. 1921 Influence of sulfur oxidation upon growth of soybeans and its effect on bacterial flora of soil. *In* Soil Sci., v. 14, p. 247–264.

(18) Rudolfs, W. 1922 Sulfur oxidation in "black alkali" soils. *In* Soil Sci., v. 13, p. 215–229.

(19) Starkey, Robert L. 1924 Concerning the physiology of Thiobacillus, Thiooxidans, and autotrophic bacterium oxidizing sulfur under acid conditions. *In* Jour. Bact., v. 10, p. 135–195.

(20) Ulsch, K. 1891 Die Ueberführung der frien Salpetersaüre im Ammoniak durch Wasserstoffim.
Statu nascendi und die Gasvolumetrische Bestimmung dieser Saüre durch Wasserstoffdeficit. *In* Ztsch. Analyt. Chem., v. 30, p. 175–195.

(21) Waksman, Selman A., Wark, Clara H., Joffe, Jacob S., and Starkey, R. L. 1923 Oxidation of sulfur by microorganisms in black alkali soil. *In* Jour. Agr. Res., v. 24, p. 297–305.

THE FORM OF LEGUME NITROGEN ASSIMILATED BY NON-LEGUMES WHEN GROWN IN ASSOCIATION[1]

JAMES HENRY STALLINGS[2]

Texas Agricultural and Mechanical College

Received for publication October 7, 1925

That non-legumes, when grown in association with inoculated legumes under favorable conditions, profit by the association is a well established fact. It is also generally conceded that this beneficial influence upon the non-legume is due to some nitrogenous substance placed at its disposal by the inoculated legume. Just what the exact nature of this nitrogenous substance is, however, is not known. The work reported in this paper was planned to throw some light upon this question.

EXPERIMENTAL

Two soils and nitrogen-free sand were used in these experiments. One of the soils was glacial in origin, occurring in the Wisconsin drift soil area, and the other was a residual soil, arising from coastal plain deposits, and occurring in the coastal plain soil area. One, classified by the Bureau of Soils as Carrington loam, was used for series I, and the other, classified as Lufkin fine sandy loam, was used for series II and III. These soils vary widely in their general characteristics and crop-producing power. The former is dark brown to black in color, well supplied with humus and nitrogen, and is considered to be a very productive soil; the latter is grayish to grayish-brown in color, low in humus and nitrogen, and is considered to be a very unproductive soil. Analysis showed 0.3408 per cent nitrogen in the Carrington loam. Analysis of the Lufkin fine sandy loam showed 0.0788 per cent nitrogen, 0.037 per cent total phosphoric acid, 1.16 per cent potash, 0.32 per cent acid-soluble lime, 0.28 per cent acid-soluble magnesia, 0.08 per cent sulfur trioxide, and by the Truog method, a lime requirement of 1 ton.

Soybeans and wheat, grown alone and in association, were the plants used. Each series except the nitrogen-free sand series consisted of 14 pots. For series I, II, and III, 2-, 3-, and 1-gallon pots, respectively, were used. The 2-gallon pots were used during the early part of the experiment but 3-gallon

[1] Part of the thesis submitted to the Faculty of the Iowa State College in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2] The writer wishes to express his appreciation to Dr. P. E. Brown for suggestions concerning the work and the manuscript and to Dr. L. W. Erdman for suggestions concerning the preparation of the manuscript.

pots were used later for the unsterilized, and 1-gallon for the sterilized soil. The soil was sterilized by autoclaving at 15 pounds for 1 hour. All inoculated soils received cultures containing the proper bacteria to bring about inoculation.

Large samples of the two soils were secured from the field, sieved, thoroughly mixed, and placed directly in the pots and weighed. The 3-gallon pots were filled with 15 kilos, the 2-gallon with 10 kilos and the 1-gallon with 5 kilos of air-dried soil. Soybeans and wheat were seeded in the pots of series I, II, and III, as shown in table 1.

The 2- and 3-gallon pots were allowed two and three times the number of plants, respectively, as in table 1.

TABLE 1

System of numbering pots and rates of seeding wheat and soybeans in series III

POT NUMBER	TREATMENT
	First harvest
1	Wheat, 6 plants, grown alone
2	Soybeans, 4 plants, grown alone
3	Wheat, 3 plants, grown with soybeans
4	Soybeans, 2 plants, grown with wheat
CK	Check, uncropped
	Second harvest
5	Wheat, 6 plants, grown alone
6	Soybeans, 4 plants, grown alone
7	Wheat, 3 plants, grown with soybeans
8	Soybeans, 2 plants, grown with wheat
CK	Check, uncropped
Orig.	Original soil

Pure cultures of the soybean organism were added to each pot and the moisture content was brought up to the optimum by adding water to weight. The moisture content was kept up during the continuance of the experiment by weighing the pots twice each week and adding distilled water to weight. The 1-gallon pots were numbered and planted as shown in table 1.

In each test the crops were harvested from duplicate pots at two stages of growth. The first harvest was made from pots 1 to 6 inclusive when the first blooms appeared on the soybeans. The second harvest was made from pots 7 to 12 inclusive when the first pods were about half mature. The soil in the check pots was sampled at both harvests. The plants were cut near the surface of the soil, and the roots carefully removed from the soil. The tops, roots, and nodules were dried and weighed. They were then finely ground and the soil, tops, roots, and nodules analysed for ammonia, nitrites, nitrates, amino acids, and total nitrogen. Duplicate determinations were

made on each sample, except in cases where there was an insufficient amount of the sample, and the results were required to agree very accurately. Repeats as well as blank determinations on reagents were run in all necessary cases. The results given in the tables are the averages of duplicate determinations on duplicate pots.

A coarse white sand was used in the nitrogen-free sand series. Eight 1-gallon pots were filled with 5 kilos of sand after mixing in 10 gm. of pure calcium carbonate. The plants in each pot received the following fertilizer treatment each week:

10 cc. each of:	25 gm.	$CaH_4(PO_4)_2$	per 2,500 cc. water
	20 gm.	$MgSO_4$	per 2,500 cc. water
	50 gm.	K_2SO_4	per 2,500 cc. water
1 cc. of:	0.1 gm.	$FeCl_3$	per 250 cc. water

These amounts were diluted with water and added to the plants.

Each pot was planted to 6 soybeans, the beans in the last 6 pots being inoculated with a pure culture solution before planting.

The roots, and the sand immediately around the roots, in pots 1 and 2, which were not inoculated, were analyzed for ammonia, nitrites, nitrates, and amino acid nitrogen. The same was done for pots 3 and 4 just at the time when the plants recovered from the period of "nitrogen hunger." The plants in the other 4 pots were harvested at the same stages as those of the soil and handled in a similar manner.

METHODS

Total nitrogen. For all total nitrogen determinations the copper sulfate method was used. A 10-gm. sample of soil, a 0.5- to 1-gm. sample of tops and roots, and a 0.1–0.5-gm. sample of nodules were used. The samples were carefully weighed in duplicates, where the amount of material was sufficient, and transferred to an 800-cc. Kjeldahl flask. About 10 gm. of a mixture of potassium sulfate and copper sulfate—100 gm. of potassium sulfate to 10 gm. of copper sulfate—was added and then from 25 to 30 cc. of concentrated sulfuric acid. The remainder of the process was the same as with any total nitrogen determination by the distillation method. For titrating, 0.05*N* sulfuric acid and 0.025*N* sodium hydroxide were used. Sodium alizarine sulfonate indicator was used throughout.

Ammonia. The colorimetric method for determining ammonia, as outlined in Bureau of Soils Bulletin 31, was used for determining the ammonia in both soil and plants.

Nitrites. The colorimetric method for determining nitrites, as outlined in Bureau of Soils Bulletin 31, was used for determining the nitrites in both soil and plants.

Nitrates. Davis' modification of the phenoldisulfonic acid method for determining nitrates in soils[3] was used for both plants and soils.

Amino acids. For the determination of amino acid nitrogen the Van Slyke method[4] was used.

Soil solutions. The soil was first air-dried, finely ground, and thoroughly mixed. One hundred-gram portions were carefully weighed into 800-cc. bottles. About 10 gm. of carbon black, special brand G. Elf., and 200 cc. of distilled water were added. The contents were

[3] Outlined in Jour. Indus. and Engin. Chem., v. 9, p. 290–295.

[4] Outlined in Jour. Biol. Chem., v. 9, p. 185–191.

shaken for 30 minutes and filtered through double folded filter paper, the first 50-cc. portions of the filtrate being discarded or poured back into the bottle for refiltering. This usually gave a clear solution.

Plant extract solution. The tops, roots, and nodules, were first dried in an electric oven and finely ground in a small grinding machine or mill. Samples were weighed, varying in size from a fraction of a gram to 10 gm., depending upon the amount of substance available, and transferred to 800-cc. shaker bottles, 500 cc. of distilled water and about 10 gm. of carbon black, special brand G. Elf., being added. The contents were shaken vigorously for about three minutes and allowed to stand for about twenty minutes with occasional shaking. The filtering was done as in the case of the aforementioned soil. The solution was then ready for use.

Series I

In this series soybeans and wheat were grown alone, and in association, on Carrington loam. The weights of tops, roots, nodules, and plants secured at the first and second harvests are given for each pot in table 2.

TABLE 2

Dry weight of plants grown in Carrington loam

POT NUMBER	TREATMENT	TOPS	ROOTS	NODULES	PLANTS
		gm.	gm.	gm.	gm.
	First harvest				
1	Wheat	12.84	12.59	....	25.88
2	Soybeans	22.36	12.48	2.25	37.09
3	Wheat with soybeans	6.72	5.61	....	9.33
4	Soybeans with wheat	10.65	5.42	*	16.08
	Second harvest				
5	Wheat	33.00	27.00	....	60.00
6	Soybeans	78.50	14.25	4.75	97.50
7	Wheat with soybeans	10.00	6.50	....	16.50
8	Soybeans with wheat	49.50	4.50	2.90	56.90

* Weight of nodules lost.

The yields given in table 2 show that the combined weight of tops and plants of soybeans and wheat grown in association was greater than wheat, but less than soybeans, grown alone. This was to be expected, since it is generally conceded that non-legumes derive considerable benefit from inoculated legumes when grown in association under favorable conditions. In the case of the roots the combined weight of soybeans and wheat grown in association was less than of soybeans and wheat grown alone.

The data given in table 3 show the amount of ammonia in the soil, tops, roots, and nodules at the first and second harvests.

An examination of this table shows that ammonia was present more or less abundantly in the soil, tops, roots, and nodules at both harvests. The soil cropped to the soybean-wheat mixture contained more ammonia than that

cropped to soybeans but less than that cropped to wheat alone at the first harvest. The soil of the soybean-wheat mixture contained an average of 0.0252 p.p.m. as compared with 0.0263 for the soybeans and 0.0801 for wheat alone at the second harvest.

The wheat tops grown in association with soybeans contained an average of 71.16 and 20.04 p.p.m. of ammonia as against 43.75 and 10.35 p.p.m. for wheat tops grown alone at the first and second harvests, respectively. The amounts of ammonia for the corresponding soybeans were 27.77 and 11.84 p.p.m. for the soybeans grown in association with wheat as against 32.88 and 14.86 p.p.m. for soybeans grown alone at the first and second harvests, respectively.

TABLE 3

Ammonia in soil, tops, roots, and nodules obtained in series I

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0413	43.75	15.70	.....
2	Soybeans	0.0323	32.88	10.18	138.85
3	Wheat with soybeans	0.0357	71.16	40.47	.....
4	Soybeans with wheat	0.0357	27.77	10.67	92.07
CK	Check	0.0728	.....	.....	.....
	Second harvest				
5	Wheat	0.0801	10.35	4.74	.....
6	Soybeans	0.0263	14.86	6.49	47.96
7	Wheat with soybeans	0.0252	20.04	10.55	.....
8	Soybeans with wheat	0.0252	11.84	17.22	56.21
CK	Check	0.0331	.....	.....	.....
Orig.	Original soil	0.1492	.....	.....	.....

The difference between the ammonia content of the roots of the wheat plants grown in association with soybeans and those grown alone, was as pronounced as that of the tops. The roots of the wheat plants grown in association with soybeans contained 40.47 and 10.55 p.p.m. of ammonia as compared with 15.70 and 4.74 p.p.m. for wheat grown alone at the first and second harvests, respectively. The amounts of ammonia for the roots of the corresponding soybeans were 10.67 and 17.22 p.p.m. for soybeans grown in association with wheat as compared with 10.18 and 6.49 p.p.m. for soybeans grown at the first and second harvests, respectively. The tops and roots of wheat plants grown in association with soybeans contained more ammonia at both harvests than those of corresponding wheat plants grown alone.

The nodules showed the presence of an abundance of ammonia in all cases. The nodules of the first harvest had a higher ammonia content than those of

the second. The ammonia content of the nodules from the soybean plants grown alone was considerably higher than that of soybean plants grown in association with wheat for the first harvest, but for the second those from the soybean plants grown in association with wheat averaged a little higher than those from the soybean plants grown alone.

In table 4 are contained the amounts of nitrites in the soil, tops, roots, and nodules for each pot at both harvests. There were no striking differences in the nitrite content of the soil of the different pots at the first harvest. The soil in which the soybeans and wheat were grown in association contained 0.0104 p.p.m. as against 0.0125 and 0.0080 p.p.m. for soybeans and wheat grown alone, respectively, for the second harvest.

TABLE 4

Nitrites in soil, tops, roots, and nodules obtained in series I

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0010	5.8785	0.0660	.....
2	Soybeans	0.0011	0.2920	0.1527	20.49
3	Wheat with soybeans	0.0011	1.1040	0.3220	.....
4	Soybeans with wheat	0.0011	0.1980	0.0794	20.49
CK	Check	0.0014	.....	.....	.....
	Second harvest				
5	Wheat	0.0080	0.0046	0.3185	.....
6	Soybeans	0.0125	0.0075	0.4524	9.04
7	Wheat with soybeans	0.0104	0.0092	0.3518	.....
8	Soybeans with wheat	0.0104	0.0056	5.8905	3.85
CK	Check	0.0146	.....	.....	.....
Orig.	Original soil	0.0016	.....	.....	.....

The wheat tops grown in association with soybeans contained an average of 1.104 and 0.0092 p.p.m. as compared with 5.87 and 0.0046 p.p.m. of nitrites for wheat tops grown alone at the first and second harvests, respectively. The corresponding soybean plants contained 0.198 and 0.0056 p.p.m. of nitrites in tops when grown in association with wheat, and 0.292 and 0.0075 p.p.m. of nitrites for soybeans grown alone at the first and second harvests, respectively. The average nitrite content of wheat roots grown in association with soybeans was 0.322 and 0.3518 p.p.m. as compared with 0.066 and 0.3185 p.p.m. for the roots of wheat grown alone for the first and second harvests, respectively. The nitrite content of the roots of the corresponding soybeans was 0.0794 and 5.89 p.p.m. for soybeans in association with wheat, and 0.1527 and 0.4524 p.p.m. for soybeans grown alone at the first and second harvests, respectively.

The soybean nodules contained nitrites in all cases, the amount being much lower at the second harvest than at the first, and considerably less for the nodules grown in association with wheat than those grown alone at the second harvest. The difference in the nitrite content of the nodules of the soybean plants grown in association with wheat, and alone, was only very slight for the first harvest.

Table 5 contains the amounts of nitrates in the soil, tops, roots, and nodules for each pot at both harvests. An examination of this table reveals the fact that the nitrate content of the soil in the soybean-wheat pots was slightly greater than that of the wheat and less than that of the soybean pots at the time of both harvests. The difference was more pronounced at the second than at the first harvest.

TABLE 5

Nitrates in soils, tops, roots, and nodules obtained in series I

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0027	54.85	10.02	.....
2	Soybeans	0.0039	4.79	22.23	None
3	Wheat with soybeans	0.0035	62.95	35.89	.....
4	Soybeans with wheat	0.0035	6.38	19.01	None
CK	Check	0.0453	.....	.....	.....
	Second harvest				
5	Wheat	0.0875	2.58	1.02	.....
6	Soybeans	0.1310	2.78	3.38	None
7	Wheat with soybeans	0.1251	7.14	1.91	.....
8	Soybeans with wheat	0.1251	2.14	2.64	None
CK	Check	1.3333	.....	.....	.....
Orig.	Original soil	0.0400	.....	.....	.....

The average nitrate content of the wheat tops grown in association with soybeans was 62.95 and 7.14 p.p.m. as compared with 54.85 and 2.58 p.p.m. for wheat grown alone at the first and second harvests, respectively. The average nitrate content of the tops for the corresponding soybean pots was 6.38 and 2.14 p.p.m. where soybeans were grown with wheat, and 4.79 and 2.78 p.p.m. where soybeans were grown alone at the first and second harvests, respectively.

The nitrate content of the roots of wheat grown with soybeans was greater at both harvests than that of wheat roots grown alone. The reverse was true for the soybeans. The roots of the soybeans grown in association with wheat contained 19.01 and 2.64 p.p.m. of nitrates as compared with 22.23 and 3.38 p.p.m. at the first and second harvests, respectively. The nodules were free from nitrates in all cases.

The data presented in table 6 show the amounts of amino acids in the soil, tops, roots, and nodules obtained in series I. An examination of this table reveals the absence of amino acids in the soil in all samples. The wheat tops contained a higher amino acid content than the soybean, except in case of the wheat tops of the soybean-wheat mixture at the second harvest when the soybean tops had a slightly larger amount of amino acid than the wheat. This difference was very slight, however. The amino acid content of the wheat tops in the soybean-wheat mixture was slightly greater than that of the wheat alone for the first harvest and less for the second. The soybean tops of the soybean-wheat mixture had a higher amino acid content than those grown alone.

TABLE 6

Amino acid nitrogen in soil, tops, roots, and nodules obtained in series I

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		cc. N	*cc. N*	*cc. N*	*cc. N*
	First harvest				
1	Wheat	None	14.61	2.76	.....
2	Soybeans	None	8.00	3.90	121.36
3	Wheat with soybeans	None	15.11	2.11	.....
4	Soybeans with wheat	None	8.09	1.69	85.00
CK	Check	None	.....	....	.....
	Second harvest				
5	Wheat	None	7.05	0.09	.....
6	Soybeans	None	2.66	0.00	17.95
7	Wheat with soybeans	None	4.75	0.50	.....
8	Soybeans with wheat	None	4.66	1.97	13.10
CK	Check	.....	.....	....	.....
Orig.	Original soil	.....	.....	....	.....

There was nothing significant about the amino acid content of the roots other than that it was much lower for the roots than for the tops, and that the roots of the second harvest contained considerably less amino acid than those of the first.

Amino acid was present in the nodules in all cases. The amount was greater with the first harvest than with the second and also greater for the soybeans alone than for the soybeans in the soybean-wheat mixture.

In table 7 are contained the amounts of total nitrogen in the soil, tops, roots, and nodules for each pot at both harvests. An examination of this table reveals a loss of nitrogen in all cropped soil over the original and checks. The loss was greater at each harvest with the soil planted to wheat alone than with soybeans alone or with the soybean-wheat mixture. The loss for the latter was less than that for the soybean alone at the first harvest and practically the same at the second.

The soybean tops had a higher percentage of total nitrogen than the wheat tops. The percentage of nitrogen was greater at the second harvest than at the first. The wheat tops of the soybean-wheat mixture were slightly lower in nitrogen at both harvests than the wheat alone. The wheat tops of the second harvest had a lower nitrogen content than those of the first.

The wheat roots grown in association with soybeans contained a higher percentage of nitrogen than those of wheat grown alone at both harvests. The nitrogen content of soybeans roots was slightly higher at the first than at the second harvest.

The nodules were exceptionally high in total nitrogen and those of the second harvest contained more nitrogen than those of the first. The association of

TABLE 7

Total nitrogen in soil, tops, roots, and nodules obtained in series I

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		per cent	*per cent*	*per cent*	*per cent*
	First harvest				
1	Wheat	0.3094	2.14	2.08	....
2	Soybeans	0.3190	3.44	2.74	7.85
3	Wheat with soybeans	0.3254	2.02	2.15	....
4	Soybeans with wheat	0.3254	3.33	2.41	7.79
CK	Check	0.3324	....	....	....
	Second harvest				
5	Wheat	0.2881	1.93	1.53	....
6	Soybeans	0.3085	3.63	2.14	9.81
7	Wheat with soybeans	0.3087	1.88	2.55	....
8	Soybeans with wheat	0.3087	3.68	2.21	9.58
CK	Check	0.3367	....	....	....
Orig.	Original soil	0.3408	....	....	....

soybeans with wheat did not seem to influence the nitrogen content of the nodules.

Series II

In this series soybeans and wheat were grown alone and in association on unsterilized Lufkin fine sandy loam. The weights of the tops, roots, nodules, and plants obtained from the first and second harvests, are given for each pot in table 8.

An examination of this table shows that the combined weight of the tops of wheat and of soybeans grown in association was greater than that of wheat but less than that of soybeans grown alone at both harvests. The combined weight of the roots of wheat and of soybeans grown in association was greater than that of soybeans but less than that of wheat grown alone at both harvests.

The average weight of nodules for each of the plants grown in association with wheat was slightly higher than for those grown alone, for the first harvest, but slightly lower for the second. The average combined weight of the plants of the soybean-wheat mixture was greater than that of wheat or soybeans grown alone at both harvests.

In table 9 are contained the amounts of ammonia, in parts per million, found in the soil, tops, roots, and nodules for each pot at both harvests. At the time of the first harvest the average ammonia content of the soil was 0.1036 p.p.m. for wheat grown alone, 0.0539 for soybeans grown alone, and 0.047 for wheat and soybeans grown in association. At the time of the second harvest the ammonia content of the soil was reversed, being a trace, 0.0093, and 0.0168 p.p.m. for wheat grown alone, for soybeans alone, and for wheat and soybeans in association, respectively.

TABLE 8

Dry weight of plants grown in unsterilized Lufkin fine sandy loam

POT NUMBER	TREATMENT	TOPS	ROOTS	NODULES	PLANTS
		gm.	*gm.*	*gm.*	*gm.*
	First harvest				
1	Wheat	8.52	10.40	....	18.92
2	Soybeans	15.80	3.76	0.79	20.36
3	Wheat with soybeans	5.85	8.10	....	13.95
4	Soybeans with wheat	8.75	1.56	0.76	11.07
	Second harvest				
5	Wheat	14.15	24.35	....	38.50
6	Soybeans	27.30	7.10	2.09	36.49
7	Wheat with soybeans	8.40	16.15	....	24.55
8	Soybeans with wheat	13.05	1.85	0.98	15.88

With the exception of the wheat tops of pot 1, in which case a poor grade of carbon black was used in decolorizing the plant extract, the wheat plants, both tops and roots, grown in association with soybeans contained more ammonia than the tops and roots of corresponding wheat plants grown alone at both harvests. The wheat tops grown in association with soybeans contained an average of 5.51 and 3.13 p.p.m. as compared with 24.94 and 1.58 p.p.m. for wheat tops grown alone at the first and second harvests, respectively. The corresponding wheat roots contained 16.70 and 1.92 p.p.m. for wheat grown in association with soybeans, and 9.60 and 0.04 p.p.m. for wheat grown alone at the first and second harvests, respectively.

The average ammonia content of soybean tops grown alone was greater with each harvest than that of soybeans grown with wheat. The soybean tops grown alone contained 10.56 and 3.39 p.p.m. as compared with 8.75 and 2.78 p.p.m. for soybean tops grown with wheat, respectively. The reverse was true

TABLE 9

Ammonia in soil, tops, roots, and nodules obtained in unsterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1*	Wheat	0.1036	24.94	9.60	.....
2	Soybeans	0.0539	10.56	14.02	48.18
3	Wheat with soybeans	0.0470	5.51	16.70	.....
4	Soybeans with wheat	0.0470	8.75	28.85	33.65
CK	Check	0.0360	....	....	.....
	Second harvest				
5	Wheat	Trace	1.58	0.04	.....
6	Soybeans	0.0093	3.39	1.43	9.91
7	Wheat with soybeans	0.0168	3.13	1.92	.....
8	Soybeans with wheat	0.0168	2.78	5.63	14.14
CK	Check	0.0039	.....	.....	.....
Orig.	Original soil	0.0062	.....	.....	.....

* The water extract of the soil and wheat tops of pot 1 were decolorized with a poor grade of carbon black which failed to remove all the coloring matter and to produce a clear solution. The readings are, therefore, too high.

TABLE 10

Nitrites in soil, tops, roots, and nodules obtained in the unsterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	None	None	None	.....
2	Soybeans	None	None	None	None
3	Wheat with soybeans	None	None	None	.....
4	Soybeans with wheat	None	None	None	None
CK	Check	0.0391	.....	.....	.....
	Second harvest				
5	Wheat	Trace	None	None	.....
6	Soybeans	0.0191	1.12	0.31	None
7	Wheat with soybeans	0.0362	None	0.20	.....
8	Soybeans with wheat	0.0362	0.23	6.78	None
CK	Check	Trace	.....	.....	.....
Orig.	Original soil	*	.....	.....	.....

*Reading lost.

with the roots. Soybean roots grown alone contained 14.02 and 1.43 p.p.m. of ammonia as compared with 28.85 and 5.63 p.p.m. for the corresponding plants grown with wheat. The nodules contained an abundance of ammonia in all cases, but those of the first harvest contained a much greater amount of ammonia than those of the second.

In table 10 are given the results of the nitrite determinations made on the soil, tops, roots and nodules at the first and second harvest, of the unsterilized Lufkin fine sandy loam series. An examination of this table reveals the absence of nitrites in the soil, tops, roots, and nodules at the first harvest in all samples, except the soil of the check pots.

TABLE 11

Nitrates in soil, tops, roots, and nodules obtained in the unsterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0312	11.66	None	.....
2	Soybeans	0.0016	Trace	1.89	None
3	Wheat with soybeans	None	4.26	5.14	.....
4	Soybeans with wheat	None	3.79	None	None
CK	Check	1.8875	.....	.....	.....
	Second harvest				
5	Wheat	None	None	None	.....
6	Soybeans	None	None	None	None
7	Wheat with soybeans	None	None	None	.....
8	Soybeans with wheat	None	None	None	None
CK	Check	0.4836	.....	.....	.....
Orig.	Original soil	0.1366	.....	.....	.....

The nitrite content of the soil at the second harvest was 0.0362 p.p.m. for the soybean-wheat mixture and 0.0191 and a trace for the soybeans and wheat alone, respectively, as compared with a trace for the checks.

The tops of wheat grown alone and in association with soybeans were free from nitrites. This was also true with the roots, except for those of pot 7 in which wheat was grown with soybeans. The roots in this case contained 0.2 p.p.m. of nitrites. The soybean tops and roots contained nitrites when grown alone and in association. The nodules were free from nitrites in all samples.

The results of the nitrate determinations on the soil, tops, roots, and nodules at the first and second harvests, found in table 11, show the absence of nitrates from all nodules at both harvests and from all soil, except that of the check pots, and from all crops, tops, and roots at the second harvest. A further

examination of this table reveals the absence of any regularity in the presence or absence of nitrates in soil, tops, and roots of plants.

In table 12 are contained the results of the amino acid nitrogen determinations made on the soil, tops, roots and nodules for each pot in the unsterilized Lufkin fine sandy loam series. This table shows the absence of amino acids in all soils and in all wheat tops, and the presence of it in all soybean tops of both harvests. It was present only occasionally in the soybean and wheat roots and soybean nodules.

Table 13, which contains the amounts of total nitrogen in the soil, tops, roots, and nodules for each pot at both harvests, reveals a loss of nitrogen in all

TABLE 12

Amino acid nitrogen in soil, tops, roots, and nodules obtained in the unsterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		cc. N	*cc. N*	*cc. N*	*cc. N*
	First harvest				
1	Wheat	None	None	0.08	.....
2	Soybeans	None	0.47	None	None
3	Wheat with soybeans	None	None	None	.....
4	Soybeans with wheat	None	0.47	None	2.67
CK	Check	None	.....	.....	.....
	Second harvest				
5	Wheat	None	None	None	.....
6	Soybeans	None	0.53	None	0.88
7	Wheat with soybeans	None	None	0.17	.....
8	Soybeans with wheat	None	0.70	None	None
CK	Check	None	.....	.....	.....
Orig.	Original soil	None	.....	.....	.....

cropped soils over the original and checks. At each harvest the loss was greater in the soil planted to wheat alone than in that planted to soybeans alone or to the soybean-wheat mixture. The loss of nitrogen was greater with the soybean-wheat mixture than with the soybeans alone for the first harvest but slightly less for the second.

With the exception of the wheat tops in pot 1 the soybean tops had a higher percentage of nitrogen than the corresponding wheat tops. The tops and the roots of the wheat grown with soybeans contained a higher percentage of nitrogen than those grown alone, and those of the soybeans grown alone showed a higher percentage than those of soybeans grown with wheat.

The nodules of this series were higher in nitrogen than those of series III, but much lower than those of series I, in which Carrington loam soil was used.

The average total nitrogen in the nodules was slightly higher for the soybeans grown alone than for those grown with wheat, and higher at the first harvest than at the second.

TABLE 13

Total nitrogen in soil, tops, roots, and nodules obtained in the unsterilized Lufkin fine sandy loam soil series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		per cent	*per cent*	*per cent*	*per cent*
		First harvest			
1	Wheat	0.0663	3.18	1.30	....
2	Soybeans	0.0739	2.50	1.60	4.04
3	Wheat with soybeans	0.0694	2.09	1.13	....
4	Soybeans with wheat	0.0694	2.32	1.37	3.99
CK	Check	0.0641	....	....	....
		Second harvest			
5	Wheat	0.0632	1.30	0.85	....
6	Soybeans	0.0684	2.25	1.66	3.83
7	Wheat with soybeans	0.0694	1.84	0.96	....
8	Soybeans with wheat	0.0694	1.98	1.62	3.71
CK	Check	0.0744	....	....	....
Orig.	Original soil	0.0788	....	....	....

TABLE 14

Dry weight of plants grown in sterilized Lufkin fine sandy loam

POT NUMBER	TREATMENT	TOPS	ROOTS	NODULES	PLANTS
		gm.	*gm.*	*gm.*	*gm.*
		First harvest			
1	Wheat	5.26	11.35	....	16.60
2	Soybeans	6.60	2.39	0.23	9.22
3	Wheat with soybeans	2.33	2.87	....	5.21
4	Soybeans with wheat	5.45	1.05	0.26	6.77
		Second harvest			
5	Wheat	6.95	25.60	....	32.55
6	Soybeans	8.85	2.18	0.28	11.31
7	Wheat with soybeans	3.71	5.19	....	8.90
8	Soybeans with wheat	8.10	1.60	0.41	10.11

Series III

In this series soybeans and wheat were grown alone and in association on sterilized Lufkin fine sandy loam. The weights of tops, roots, nodules, and plants secured are given for each pot in table 14. An examination of the

yields in this table shows that the combined weight of the tops of wheat and soybeans grown in association was greater than that of wheat and of soybeans grown alone. The combined weight of the roots and plants of wheat and soybeans grown in association was greater than that of soybeans but less than that of wheat grown alone. The average weight of the nodules from soybeans grown with wheat was greater than that of nodules from soybeans grown alone at both harvests.

Table 15 gives the amounts of ammonia in the soil, tops, roots, and nodules for each pot at both harvests. Here, as with the data for the soil and tops of pot 1 in table 9, series II, the readings of ammonia for soil, tops, and roots of

TABLE 15

Ammonia in soil, tops, roots, and nodules obtained in the sterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1*	Wheat	0.0865	20.54	12.20	.....
2	Soybeans	0.0391	4.62	10.38	29.64
3	Wheat with soybeans	0.0322	6.10	7.11	.....
4	Soybeans with wheat	0.0322	4.63	11.42	34.00
CK	Check	0.0518	.....	.....	.....
	Second harvest				
5	Wheat	None	2.50	0.28	.....
6	Soybeans	0.0429	4.41	3.96	16.00
7	Wheat with soybeans	0.0224	7.85	5.03	.....
8	Soybeans with wheat	0.0224	4.30	5.73	13.97
CK	Check	0.0104	.....	.....	.....
Orig.	Original soil	0.0835	.....	.....	.....

* The water extract of the soil and plants of pot 1 were decolorized with a poor grade of carbon black which failed to produce a clear solution. The readings of ammonia are, therefore, too high.

pot 1 were too high, because of the use of the same poor grade of carbon black for decolorizing the soil and plant extracts. With this exception the tops and roots of the wheat plants grown in association with soybeans contained larger amounts of ammonia than those of the wheat plants grown alone. The wheat tops grown in association with soybeans contained an average of 6.10 and 7.85 p.p.m. of ammonia, whereas the tops of the wheat grown alone in corresponding pots contained 20.54 and 2.50 p.p.m. for the first and second harvests, respectively. With one exception the wheat tops contained a larger amount of ammonia than the corresponding soybean tops. The wheat roots corresponding to the aforementioned tops contained an average of 7.11 and

5.03 p.p.m. of ammonia for those grown with soybeans, and 12.20 and 0.28 p.p.m. for those grown alone. With one exception, the soybean roots contained a larger amount of ammonia than the corresponding wheat roots. The nodules showed an abundance of ammonia in all cases.

With the exception of the soil of pot 1, the ammonia content of the wheat soil was lower than that of the soybean-wheat mixture and of the soybeans alone at both harvests. The soybean soil had more ammonia than the soil of the soybean-wheat mixture.

Table 16 gives the results of the nitrite determinations made on the soil, tops, roots, and nodules at the first and second harvests of the sterilized Lufkin fine sandy loam series. An examination of this table reveals the absence of nitrites from all cropped soils, except one wheat and one soybean soil. The

TABLE 16

Nitrites in soil, tops, roots, and nodules obtained in the sterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0186	None	None	.....
2	Soybeans	None	None	None	None
3	Wheat with soybeans	None	None	None	.....
4	Soybeans with wheat	None	None	None	None
CK	Check	Trace	.....	.....	.....
	Second harvest				
5	Wheat	None	None	None	.....
6	Soybeans	0.0023	0.03	1.63	6.62
7	Wheat with soybeans	None	0.14	0.70	.....
8	Soybeans with wheat	None	0.11	1.57	2.36
CK	Check	0.0008	.....	.....	.....
Orig.	Original soil	0.1746	.....	.....	.....

amount of nitrites present in these soils was very small. Nitrites were absent from all samples of plants at the first harvest.

The tops and roots of wheat grown alone at the second harvest were free from nitrites, whereas those of the soybean-wheat mixture showed fairly large amounts. The soybean tops of this harvest contained small amounts of nitrites, whereas nitrites were present in fairly large quantities in the roots and nodules of the soybean plants. The average nitrite content of the roots and nodules of soybeans grown alone was greater than that of soybeans grown with wheat.

The results for the nitrate determinations on the soil, tops, roots, and nodules for each pot in series III are found in table 17. An examination of the results in this table shows that nitrates were present in only one cropped soil,

in the checks, and in the original. A further examination of this table reveals the fact that nitrates were also absent from all soybean and wheat tops, as well as from the wheat roots and from the soybean nodules of both harvests. Nitrates were present only in the soybean roots from pots 4, 6, and 8.

In table 18 are presented the results of the amino acid determinations made on the soil, tops, roots, and nodules for each pot in the sterilized Lufkin fine sandy loam series. An examination of this table shows that amino acids were absent from all soil, from all wheat tops, and from all soybean nodules of both harvests, whereas they were present in all soybean tops of both harvests and in the roots of pots 2, 3, and 4.

Table 19 contains the amounts of total nitrogen in soil, tops, roots, and nodules for each pot in series III. An examination of this table reveals a

TABLE 17

Nitrates in soil, tops, roots, and nodules obtained in the sterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
	First harvest				
1	Wheat	0.0376	None	None	.....
2	Soybeans	None	None	None	None
3	Wheat with soybeans	None	None	None	.....
4	Soybeans with wheat	None	None	4.38	None
CK	Check	0.3733	.....	.....	.....
	Second harvest				
5	Wheat	None	None	None	.....
6	Soybeans	None	None	4.21	None
7	Wheat with soybeans	None	None	None	.....
8	Soybeans with wheat	None	None	1.76	None
CK	Check	0.2295	.....	.....	.....
Orig.	Original soil	0.0364	.....	.....	.....

loss of nitrogen from all soils over the original. The loss was less at each harvest in the soils planted to wheat than in those planted to wheat and soybeans in association, or to soybeans alone. The loss was much greater at the second harvest than at the first. The difference between the loss of nitrogen from the soils planted to wheat and soybeans in association and to soybeans and wheat alone was very slight. The tops and roots of wheat grown in association with soybeans had a higher percentage of nitrogen than the tops and roots of corresponding wheat plants grown alone.

The nitrogen content of the nodules was higher than that of the tops and roots of the soybean plants, but much lower on the average than that for the nodules of the unsterilized soil in series II. The nodules of the second harvest were lower in nitrogen than those of the first.

TABLE 18

Amino acid nitrogen in soil, tops, roots, and nodules obtained in the sterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		cc. N	*cc. N*	*cc. N*	*cc. N*
	First harvest				
1	Wheat	None	None	None	.....
2	Soybeans	None	0.5200	1.12	None
3	Wheat with soybeans	None	None	0.20	.....
4	Soybeans with wheat	None	0.1300	0.76	None
CK	Check	None	.....	.....	.....
	Second harvest				
5	Wheat	None	None	None	.....
6	Soybeans	None	0.7600	None	None
7	Wheat with soybeans	None	None	None	.....
8	Soybeans with wheat	None	0.1600	None	None
CK	Check	None	.....	.....	.....
Orig.	Original soil	None	.....	.....	.....

TABLE 19

Total nitrogen in soil, tops, roots, and nodules obtained in the sterilized Lufkin fine sandy loam series

POT NUMBER	TREATMENT	SOIL	TOPS	ROOTS	NODULES
		per cent	*per cent*	*per cent*	*per cent*
	First harvest				
1	Wheat	0.0717	2.11	0.65	....
2	Soybeans	0.0614	2.96	1.69	3.94
3	Wheat with soybeans	0.0630	2.17	1.38	....
4	Soybeans with wheat	0.0630	2.53	2.57	3.65
CK	Check	0.0750	....	....	....
	Second harvest				
5	Wheat	0.0695	1.27	0.65	....
6	Soybeans	0.0471	2.60	1.53	2.36
7	Wheat with soybeans	0.0459	1.61	0.79	....
8	Soybeans with wheat	0.0459	2.30	1.15	3.15
CK	Check	0.0671	....	....	....
Orig.	Original soil	0.0788	....	....	....

Series IV

In this series soybeans were grown in nitrogen-free sand. Pots 1 and 2 were uninoculated while pots 3 to 8 inclusive were inoculated. The plants in pots 1 and 2 were harvested as soon as growth ceased, because of the exhaustion of the reserve food in the cotyledons. The plants of pots 3 and 4 were cut at the time when they were just recovering from the period of "nitrogen hunger." The roots and sand immediately around the roots were analyzed for the various forms of water-soluble nitrogen recorded in tables 20 to 25. The system of numbering the pots in the tables of this series was as follows: pot 1 includes uninoculated pots 1 and 2; pot 2, inoculated pots 3 and 4; pot 3, inoculated pots 5 and 6; and pot 4, inoculated pots 7 and 8. The results given in the tables are the averages of duplicate determinations on duplicate pots. The plants in pots 5 and 6 were harvested when the first blooms appeared and those of pots 7 and 8 when the first pods were about half mature. The sand, tops, roots, and nodules were analyzed for the same forms of nitrogen reported in the soil series.

The weights of tops, roots, nodules, and plants secured for each pot in series IV (table 20) show that the inoculated plants made a satisfactory growth in the nitrogen-free sand. The average yields of tops, roots, nodules, and plants increased with the age of the plant.

Table 21, which contains the amounts of ammonia in the sand, tops, roots, and nodules for each pot in series IV, shows that ammonia was present in all samples of sand and crops. The most striking feature of this table was that the sand and roots of the uninoculated pot 1 had a much higher ammonia content than those of the inoculated pots. This may be accounted for, however, by the fact that it was difficult to tell just when active growth ceased and when decomposition of the small rootlets set in with the uninoculated plants. The excessive amounts of ammonia may have been due to the ammonification of the small rootlets and may have represented the ammonia contained in the seed planted. The ammonia content of the sand was greatest with pot 1 and smallest with pot 4. The ammonia content of the sand of the inoculated pots decreased with the age of the plants.

Ammonia determinations were not made on the tops of plants in pots 1 and 2. The tops of the plants of the remaining pots showed the presence of ammonia in all cases, the average ammonia content being practically the same at both harvests.

There was a striking similarity between the ammonia content of the sand and of the roots of all pots. The roots of the uninoculated soybean plants contained an average of 60.49 p.p.m. of ammonia as compared with 12.98, 4.00, and 4.27 p.p.m. for those of the soybeans harvested at the "nitrogen hunger," "first bloom," and "first pods half mature" stages, respectively.

The nodules of pots 3 and 4 showed the presence of ammonia, the amount being slightly higher for pot 3 than for pot 4.

TABLE 20

Dry weight of plants grown in the nitrogen-free sand series

POT NUMBER	TREATMENT	TOPS	ROOTS	NODULES	PLANTS
		gm.	*gm.*	*gm.*	*gm.*
1	Soybeans, uninoculated.....	.....	0.34	....	.....
2	Soybeans, inoculated.....	.....	0.89	....	.....
3	Soybeans, inoculated.....	10.77	3.55	1.35	15.68
4	Soybeans, inoculated.....	13.30	3.62	1.69	18.62

TABLE 21

Ammonia in sand, tops, roots, and nodules obtained in the nitrogen-free sand series

POT NUMBER	TREATMENT	SAND	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
1	Soybeans, uninoculated.....	0.1425	....	60.49	....
2	Soybeans, inoculated.....	0.0928	....	12.98	....
3	Soybeans, inoculated.....	0.0560	3.86	4.00	5.46
4	Soybeans, inoculated.....	0.0510	3.88	4.27	5.16

TABLE 22

Nitrites in sand, tops, roots, and nodules obtained in the nitrogen-free sand series

POT NUMBER	TREATMENT	SAND	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
1	Soybeans, uninoculated.....	Trace	....	None	....
2	Soybeans, inoculated.....	None	....	Trace	....
3	Soybeans, inoculated.....	0.0129	0.66	0.52	0.85
4	Soybeans, inoculated.....	0.0067	0.35	0.50	0.83

TABLE 23

Nitrates in sand, tops, roots, and nodules obtained in the nitrogen-free sand series

POT NUMBER	TREATMENT	SAND	TOPS	ROOTS	NODULES
		p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*
1	Soybeans, uninoculated.....	0.0175	.....	None	.....
2	Soybeans, inoculated.....	0.0125	.....	28.30	.....
3	Soybeans, inoculated.....	None	None	None	None
4	Soybeans, inoculated.....	None	None	None	None

TABLE 24

Amino acid nitrogen in sand, tops, roots, and nodules obtained in the nitrogen-free sand series

POT NUMBER	TREATMENT	SAND	TOPS	ROOTS	NODULES
		cc. N	*cc. N*	*cc. N*	*cc. N*
1	Soybeans, uninoculated.....	None	....	None	.....
2	Soybeans, inoculated.....	None	....	None	.....
3	Soybeans, inoculated.....	None	1.37	0.43	None
4	Soybeans, inoculated.....	None	1.37	0.35	None

Table 22 reveals only a trace of nitrites in the sand and "none" in the roots of the uninoculated pot. The sand of pot 2 was free from nitrites, whereas the roots contained only a trace. The sand, tops, roots, and nodules of pot 3 showed a greater nitrite content than did those of pot 4.

Table 23 shows that nitrates were absent from the sand, tops, roots, and nodules in all samples, except from the sand in pots 1 and 2 and from the roots in pot 2.

Table 24 shows that amino acids were absent from the sand and nodules of all pots, and also from the roots of pots 1 and 2. The soybean tops and roots of pots 3 and 4 revealed small quantities of amino acid nitrogen.

Table 25 shows the total nitrogen determinations for the sand, tops, roots, and nodules of pots 3 and 4. An examination of this table reveals a decided gain or fixation of nitrogen in the sand. It also shows the fact that the tops, roots, and nodules of the soybean plants contained a high percentage of nitrogen in all cases.

TABLE 25

Total nitrogen in sand, tops, roots, and nodules obtained in the nitrogen-free sand series

POT NUMBER	TREATMENT	SAND	TOPS	ROOTS	NODULES
		per cent	*per cent*	*per cent*	*per cent*
1	Soybeans, uninoculated.....	.....	....	....	....
2	Soybeans, inoculated.....	.....	....	....	....
3	Soybeans, inoculated.....	0.0163	2.74	2.64	4.34
4	Soybeans, inoculated.....	0.0150	2.93	2.91	4.51

DISCUSSION OF RESULTS

It may easily be seen from the data presented in this paper that some of the problems discussed have no direct bearing on the main object of the experiment, but they are very closely related and may supplement available data.

A careful study of the portion of the data bearing directly upon the object of this paper discloses some very interesting occurrences which, even though they may be applicable only to the conditions under which the experimental work was conducted and not to field conditions in general, if not in themselves a solution of the problem, may prove helpful in arriving at a satisfactory one.

The data presented in the foregoing pages may be summarized briefly here in order to direct attention to their more salient points.

The weights and total nitrogen of the tops, roots, nodules, and plants were of no particular significance insofar as this problem was concerned.

Ammonia was present in greater or less amounts in all samples of soil, tops, roots, and nodules of each pot in the four series. The wheat soils of both harvests of the Carrington loam and those of the first harvest of the two Lufkin fine sandy loam series had a higher ammonia content than those planted to wheat and soybeans grown in association or to soybeans alone. With one or

two exceptions there was but little difference in the ammonia content of soils planted to the soybean-wheat mixture and to soybeans alone in series I, II, and III.

With the exception of the wheat tops of the first harvest of series II and the wheat tops and roots of the same harvest of series III, in which cases a poor grade of carbon black was used to decolorize the plant extracts, the tops and roots of wheat grown in association with soybeans contained a higher ammonia content than those of corresponding wheat plants grown alone. The regularity of this difference may be a peculiar coincidence and may have no bearing on the immediate solution of the problem, but it is very striking indeed when considered in the light of a more complete discussion of the ammonia data presented here. In all instances the roots of soybeans grown with wheat contained a higher ammonia content than those of corresponding soybeans grown alone. Should the wheat plants obtain nitrogen from the soybeans in the form of ammonia their association with the latter evidently served to stimulate the production of ammonia by the soybean plant through the assistance of the nodule bacteria. With the exception of the first harvest of the sterilized Lufkin fine sandy loam series, the tops of the soybeans grown alone contained more ammonia than those of corresponding soybean plants grown with wheat. In this case the ammonia content of the soybean tops grown alone was practically the same as that of the soybean tops grown with wheat.

These data indicate that the wheat plants grown in association with soybeans had the ability to stimulate ammonia production, assimilation, or accumulation in the roots of the soybean plants. It is possible that the close relationship existing between the root systems of the two plants was such as to stimulate ammonia production by the legume bacteria. Assuming this to be the case the remaining portion of this peculiar phenomenon could be explained by the electrical theory of plant feeding, that is, if plants are capable of feeding by the electrical absorption of plus or minus ions from the soil solution, as governed by the state of equilibrium of these charges within the plant juices, it seems equally possible that if the wheat plant was capable of setting up a stronger attraction for the ammonia radicle than the soybean the wheat plant would be able to obtain it even though it were already in the roots of the soybean plants. This, of course, would mean that the ammonia, which was produced in the soybean roots, would be removed to the wheat plant instead of being allowed to pass further into the soybean plant.

The nodules contained an abundance of ammonia in all cases, the amount in each series being much greater at the first harvest than at the second. Ammonia was also present in the sand, tops, roots, and nodules of the soybeans from each pot in the nitrogen-free sand series. The sand and soybean roots from the uninoculated pot of this series contained more ammonia than those from the inoculated pots. The ammonia content of the sand and soybean roots of pot 2, harvested at the time when the plants were just recovering from the period of "nitrogen hunger," was much greater than that of pots

3 and 4 which were harvested at later periods. There were but slight differences between the ammonia content of the sand, tops, roots, and nodules of those pots harvested at the last two stages of growth.

The data obtained on nitrite nitrogen were not nearly as interesting as those of ammonia. Nitrites were present in all soils, tops, roots, and nodules of each pot in the Carrington loam series. The amount present was much larger in the soils and roots of the second harvest than those of the corresponding soils and roots of the first, and much smaller for the tops and nodules of the second than for those of the first. In contrast with this, nitrites were absent from all cropped soils of the sterilized Lufkin fine sandy loam at the first harvest, except that planted to wheat alone, and all of the unsterilized Lufkin fine sandy loam at the first harvest. The differences found here may possibly have been due to the difference in the fertility of the two types of soil.

The wheat soils of the second harvest had a trace and "none" of nitrites in series II and III, respectively. The soils of series II, in which soybeans and wheat were grown both in association and alone, contained small amounts of nitrites whereas series III contained nitrites only in the soils where soybeans were grown alone. All tops and roots of soybeans and the wheat roots of the soybean-wheat pots, of the second harvest of series II, showed nitrites to be present, whereas the other wheat roots showed them to be absent. Nitrites were present in the tops and roots of soybeans grown alone, and with wheat, and in those of wheat grown with soybeans at the second harvest of series III. They also occurred in the nodules of the second harvest of this series.

The sand of uninoculated pot 1 of the nitrogen-free sand series showed a trace of nitrites whereas that of the inoculated pot 2 did not. Nitrites were absent from uninoculated roots but were present in traces only in the roots of the inoculated pots 3 and 4 of this series. Notwithstanding the fact that nitrites occurred in all samples of inoculated soybean roots, tops and nodules of the nitrogen-free sand series, they did not always occur in similar parts of inoculated soybeans grown in the sterilized and in the unsterilized Lufkin fine sandy loam.

Nitrates were present in all soils and samples of tops and roots of wheat and soybeans in series I. They were absent from all nodules in this as well as the other three series. Nitrates were present in small amounts only in the soil in which wheat and soybeans were grown alone at the first harvest in series II, and in wheat soils of series III of the same harvest. Nitrates were present in the tops of wheat and soybeans grown alone and in association, and in the roots of soybeans grown alone, and those of wheat grown with soybeans at the first harvest of series II. All tops and roots of the second harvest of series II were free from nitrates.

In the sterilized Lufkin fine sandy loam series, nitrates were absent from all soybean and wheat tops. They were present only in the roots of soybeans of the soybean-wheat mixture of the first harvest, and in those of the soybeans grown alone and with wheat of the second.

Nitrates were present in the sand of pots 1 and 2 and the soybean roots of

pot 2 of the nitrogen-free sand series. In all other pots of this series nitrates were absent from the sand, tops, roots, and nodules.

It seems that the complete absence of nitrates from all samples of nodules and their irregular occurrence in the soil and in the tops and roots of soybeans would minimize their importance in this problem.

Amino acid nitrogen was absent from all soils in series I and III inclusive, and from the sand of series IV, and present in all samples of soybean tops of the four series. It was also present in all samples of roots of series I. All wheat tops of series II and III and all roots of series II, except those of wheat grown alone at the first harvest and those of wheat grown with soybeans at the second, were free from amino acid nitrogen. The soybean nodules of series II grown in association with wheat at the first harvest, and alone at the second, showed the presence of small quantities of amino acid nitrogen. In series III amino acid nitrogen was absent from all roots at the second harvest and from all nodules at both harvests of this series as well as from the nodules of series IV. Amino acid nitrogen was present in small amounts in the soybean roots of series IV.

CONCLUSIONS

The data obtained from these experiments seem to justify the following conclusions:

1. Ammonia was found in all soils, tops, roots and nodules of each pot in the four series.
2. With the exception of the wheat tops grown alone at the first harvest of series II and of the tops and roots of wheat grown alone at the same harvest of series III, the tops and roots of wheat grown in association with soybeans had a higher ammonia content than those of corresponding wheat plants grown alone.
3. The roots of soybeans grown in association with wheat contained a larger amount of ammonia than those of corresponding soybean plants grown alone.
4. The sand and soybean roots of the uninoculated pots of the nitrogen-free sand series contained more ammonia than did those of the inoculated pots.
5. Nitrites were found in all tops and nodules and in all roots of the inoculated pots of the nitrogen-free sand series.
6. Nitrates were not found in soybean nodules of any series, but were sometimes found in the roots of inoculated soybeans grown in nitrogen-free sand.
7. Amino acid nitrogen was not found in the soil or nitrogen-free sand, but it was found in all soybean tops of the four series, and was sometimes found in soybean nodules, in soybean and wheat roots, and in wheat tops.
8. Wheat grown in association with inoculated soybeans may, under favorable conditions, obtain considerable amounts of nitrogen from the latter without lowering the nitrogen content of the soybeans.
9. Soybeans were capable of fixing large amounts of nitrogen when grown in inoculated nitrogen-free sand.
10. Ammonia was the only form of water-soluble nitrogen found in the soil tops, roots, nodules, and nitrogen-free sand of each pot in the four series.
11. The beneficial influence exerted upon wheat by the inoculated soybeans was evidently due to soluble nitrogen, possibly ammonia, placed at the disposal of the latter by the former, when grown in association.
12. All cropped soils showed a loss of nitrogen. With the unsterilized soil this loss was greater in the soil planted to wheat alone than in the soils planted to soybeans and wheat in association or to soybeans alone, whereas in the sterilized Lufkin fine sandy loam series the loss from the soil planted to wheat alone was less than from the soil planted to soybeans and wheat in association or to soybeans alone.

EFFECTS OF SOIL TREATMENTS UPON THE DRAFT OF PLOWS[1]

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Received for publication October 23, 1925

An experiment field, now known as Sanborn field, comprising 39 plots was established at the Missouri Experiment Station in 1888 (4) on a phase of the Putnam silt loam. This field was designed primarily for studying the effects of crop rotation, of manuring, and of the use of chemical fertilizer upon the yields of crops. Because, however, of the long continued application of the same soil treatments, which differ for each plot, some of these plots have become vastly different from others both in productiveness and in physical, chemical, and biological properties. They therefore provide an excellent opportunity for making special studies concerning the effects of various soil treatments when continued throughout a long period of time.

For a number of years it has been observed that the manured plots have not worked down into as friable a seedbed as has the untreated land or the land receiving chemical fertilizers. No very satisfactory method was known for measuring this difference or for expressing it in mathematical terms. It was thought, however, that measurements of the draft of plows might show whether the manure actually made the soil harder to work. Accordingly dynamometer tests were begun on some of these plots in 1923—34 years after the soil treatments were started. Because some of the plots with the longer rotations are not plowed very often a good deal of time is required to accumulate any considerable number of measurements. Hence, this paper is presented as a progress report.

METHODS

The plowing was done during 1923 with a 14-inch Oliver Sulky plow and during 1924 and 1925 with a 16-inch P and O Sulky plow. Each plow was equipped with a general purpose bottom. The edge of the plot was opened with a two-way plot plow and measurements were made on the central portion of each plot. In most cases six or more readings were taken and the results averaged. The draft was determined by means of an Iowa integrating dynamometer. Some difficulty was experienced in getting an accurate measure on the depth of furrow, but the most satisfactory method found was to take an average of 8 to 12 measurements at 4- to 6-foot intervals over the

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50 feet of furrow included in each draft determination. In order to study the effect of the moisture upon the draft and upon the pulverizing effect, soil samples were taken from each plot at the time of plowing.

RESULTS OF DRAFT TESTS

Table 1 shows a summary of all the tests made, giving the average draft per square inch of furrow slice for each date. It will be noted that some of the plots vary widely at different plowings. This usually can be explained by the moisture content at the time of plowing or by the crop preceding. Most of the measurements have been made, however, upon plots having a single crop system. Plots 12 and 13 in the 6-year rotation series were plowed after oats. Plots 34, 35, 37, 38, and 39 in the 4-year rotation were plowed before corn in 1923 and before wheat in 1924. Plots 25 and 28, having a 3-year rotation, were plowed before corn in 1925. The first tests made on April 8, 1925 were at a higher moisture content than those made May 6. A slight source of error on these as well as on a few of the others was due to a light growth of weeds which may have affected the draft somewhat. An attempt was made to take the readings at all times as soon after removing a crop as possible so as to eliminate any error due to weed growth.

EFFECT OF MANURE

The effect of barnyard manure upon the draft is shown graphically in figure 1, in which manured plots have been compared with unmanured plots having the same crop treatment. In the case of plots 28 and 35 the land has been manured during the first 25 years, but has had no manure since. These have been used as unmanured plots for comparison with those continually manured. Plot 39 was not used in this case because it was located a considerable distance from 34. It should be noted also that plot 2, which received chemical fertilizer, has been used as an unmanured plot for comparison with no. 5. It must be remembered that these plots are comparable in pairs—manured vs. unmanured.

The upper part of figure 1 shows the results from 15 pairs of plots. In 5 cases the manured land gave a lower draft and in 10 cases it gave a higher draft than the unmanured land. When the results from each plot taken at different times are averaged the lower curves in the figure are obtained. These show that only in the case of plots 9 and 10, which are in wheat continually, was the draft decidedly lower on the manured land. Plot 13 shows a somewhat similar difference, but this was the result of but one test, as may be seen from table 1.

Noll's (5) results at Pennsylvania show a slight decrease in draft on the manured plots when these are compared with the untreated land. However, in comparing the draft with "humus" content ($C \times 1.724$), plot 22 having the highest amount of so-called "humus" gave an average of 455 pounds, the

TABLE 1

Effect of soil treatment upon the draft of plows

PLOT	TREATMENT	DRAFT PER SQUARE INCH OF FURROW SLICE						
		April 11, 1923	July 31, 1923	April 25, 1924	July 21, 1924	April 8, 1925	May 6, 1925	Average
2	Wheat annually Nitrate of soda 495.6 pounds per acre Acid phosphate 111.3 pounds per acre Muriate of potash 111.3 pounds per acre		5.46		6.08			5.77
5	Wheat annually Manure 6 tons 1889–1913 Manure 3 tons since 1914		6.35		6.24			6.29
9	Wheat annually No treatment		5.30		5.53			5.41
10	Wheat annually Manure 6 tons		5.26		4.84			5.05
12	6-year rotation Manure 6 tons 1889–1913–3 tons since 1913 Bonemeal 200 pounds on corn and on wheat		5.20					5.20
13	6-year rotation No soil treatment		5.67					5.67
17	Corn annually No treatment	4.63		5.60		5.43	5.80	5.36
18	Corn annually Manure 6 tons	5.04		6.82		5.02	6.29	5.74
21	Wheat annually Manure 1889–1913 Acid phosphate 200 pounds per acre since 1914				4.76			4.76
24	Wheat annually Manure 1889–1913 No treatment since 1913				4.60			4.60
34	4-year rotation Manure 6 tons	5.16			5.58			5.37
35	4-year rotation Manure 1889–1913 No treatment since 1913	5.00			5.52			5.26
37	4-year rotation Manure 6 tons 1889–1913 Fertilizer since 1913 300 pounds 3–10–4 on corn 200 pounds 3–10–4 on wheat	4.78			5.62			5.20
38	4-year rotation Same treatment as plot 37 but has 2 tons limestone with corn	4.78			5.64			5.21
39	4-year rotation No treatment	5.03			6.20			5.61

TABLE 1—*Continued*

PLOT	TREATMENT	DRAFT PER SQUARE INCH OF FURROW SLICE						
		April 11, 1923	July 31, 1923	April 25, 1923	July 21, 1924	April 8, 1925	May 6, 1925	Average
25	3-year rotation Manure 6 tons annually					4.74	5.70	5.22
26	3-year rotation Manure 9 tons on corn					4.29	5.29	4.79
27	3-year rotation No soil treatment					4.57	5.03	4.80
28	3-year rotation Manure 6 tons 1889–1913 No treatment since 1913					4.56	5.06	4.86

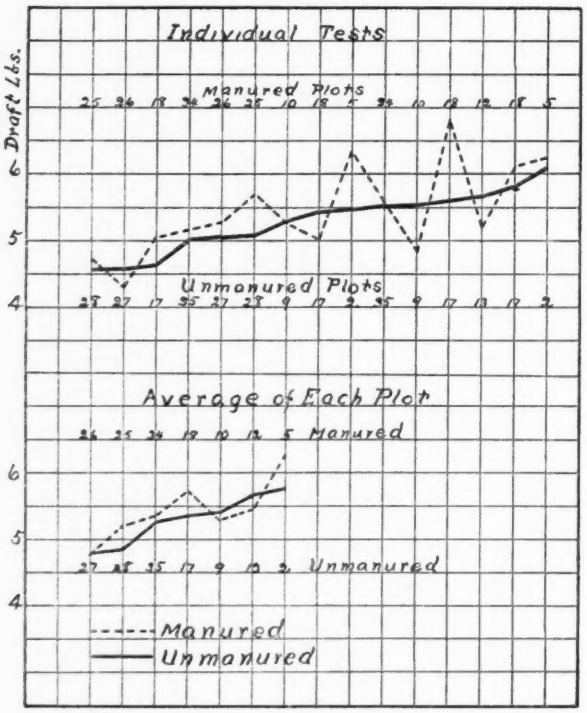

FIG. 1. COMPARISON OF THE PLOW DRAFT PER SQUARE INCH OF FURROW SLICE ON MANURED VS. UNMANURED LAND

highest draft of any of the plots; plots 20 and 21 having the next highest amount averaged 443 pounds; and plots 23 and 24 having the lowest "humus" content averaged 439 pounds.

The only explanation that can be suggested at this time as to why manure should increase the draft, is the influence exerted by the organic colloids. It seems likely that these may exert a binding effect upon the soil particles of this silt loam soil; that is, the material in an advanced stage of decomposition may exert a greater influence in binding the particles together than the undecomposed material can exert in holding them apart. As a result, the silt loam acquires some of the properties of a heavier soil and the effect upon the draft may be much the same as if clay particles had been added to the soil.

EFFECT OF FERTILIZERS AND LIME

It is a common opinion among farmers that fertilizers added to the soil will soon result in more compact soil conditions and consequent higher draft

TABLE 2

Relative effect of manure and fertilizers upon the draft of plows (4-year rotation series)

PLOT	TREATMENT	DRAFT PER SQUARE INCH APRIL 11, 1923	DRAFT PER SQUARE INCH JULY 31, 1924	AVERAGE
		pounds	*pounds*	*pounds*
34	Manure 6 tons annually 1889–1924 (35 years)	5.16	5.58	5.37
35	Manure 1889–1914 (25 years) no manure since	5.00	5.52	5.26
37	Manure 25 years, 500 pounds 3–10–4 fertilizer per rotation since	4.78	5.62	5.20
38	Same treatment as 37 + limestone 2 tons added with corn since 1914	4.78	5.64	5.21
39	No soil treatment	5.03	6.20	5.61

of plows. Some of the plots in the 4-year rotation series were manured for only the first 25 years. Fertilizers were added to one of these and fertilizer and lime were added to another. The results are shown in table 2. It will be seen that the manured land has given slightly heavier draft than the land having no manure since 1913, and furthermore the fertilized land was slightly easier to plow than the land having no fertilizer. The average results of each of plots 34 to 38 compared with 39 show that the draft on plot 39 is slightly higher. This is due chiefly to the result of 1924, a very wet season. Plot 39 being on the lower end of the series was, therefore, in a rather compact condition. Then too it is a rather long distance from plot 34 which has been manured heavily. For these reasons and particularly since it had the same treatment as the others up to 1913, plot 35 is believed to be more suitable than 39 as a check plot for determining the effect of fertilizers or manure on these plots.

A comparison of plot 2 with plot 5 in table 1 shows a similar effect of fertilizer. The former, which received chemical fertilizers, gave an average draft of 5.77 pounds whereas the latter, which received 6 tons of manure annually from 1889 to 1913 and 3 tons annually since that time, gave an average draft of 6.29 pounds. There was no untreated plot that could be compared directly with these but the results indicate that the draft was increased by the manure over the plot with chemical fertilizers. These plots, however, do not lie side by side and there is a very slight difference in slope. It seems likely, therefore, that too much emphasis should not be placed upon the results from these two plots. The figures, however, bear out the observations upon the land, since plot 2, which receives chemical fertilizers, invariably pulverizes into a much finer seedbed than does plot 5, which receives 3 tons of manure annually.

Noll (5) showed that on the Pennsylvania plots the draft was about the same on four manured plots as on plots receiving commercial fertilizer alternating with them.

The addition of lime at the rate of 2 tons an acre once in the rotation has apparently had no effect in decreasing the draft on this soil as shown by a comparison of plots 37 and 38 in table 2. This does not agree with Noll's results since he found a slight decrease in the draft due to a similar application of lime but through a longer period of years. Russell and Keen (8) also showed that 20 loads of fine chalk or 50 loads of "dug" chalk per acre reduced the draft of plows approximately 11 per cent. These are of course much heavier applications than are considered practical in America, and with relatively small amounts of liming material the effect upon draft cannot be expected to be so great.

EFFECT OF SOIL MOISTURE

Whenever dynamometer tests were made samples were taken for moisture determinations. It was believed that the effect of moisture upon draft might be considerable and that this was likely to be an important factor in causing variation under different soil treatments. Table 3 gives the moisture content of each plot at the time of the various tests. Figure 2 shows the relation between the moisture content of the soil and the draft of the plow at the time of each series of tests. It will be noted that in general the draft becomes less with the higher moisture contents, and higher whenever the ground becomes dry. Just how wide is the range of soil moisture, to which this general statement could be applied is not known, but it seems likely that it will apply fairly well on this soil to such moisture conditions as are satisfactory for plowing.

Kuhne (3) found that the draft increased with increasing dampness of a sand soil up to a certain point and thereafter decreased. In a soil dampened irregularly, the draft increased as the soil became drier. Ringelmann (7) found that for plowing, the best results were obtained when the soil which

TABLE 3

Soil moisture content of the various plots at the time dynamometer tests were made

PLOT	TREATMENT	SOIL MOISTURE					
		April 11, 1923	July 31, 1923	April 25, 1924	July 31, 1924	April 8, 1925	May 6, 1925
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
2	Wheat annually Nitrate of soda 495.5 pounds per acre Acid phosphate 111.3 pounds per acre Muriate of potash 111.3 pounds per acre		14.24		15.12		
5	Wheat annually Manure 6 tons 1889–1913 Manure 3 tons since 1914		12.55		24.25		
9	Wheat annually No treatment		10.66		20.79		
10	Wheat annually Manure 6 tons		19.38		27.13		
12	6-year rotation Manure 6 tons 1889–1913, 3 tons since 1913 Bonemeal 200 pounds on corn and wheat		12.63				
13	6-year rotation No soil treatment		7.09				
17	Corn annually No treatment	18.38		Lost		18.07	16.85
18	Corn annually Manure 6 tons	23.01		Lost		26.47	25.90
21	Wheat annually Manure 1889–1913 Acid phosphate 200 pounds per acre since 1914				25.78		
24	Wheat annually Manure 1889–1913 No treatment since 1913				25.19		
34	4-year rotation Manure 6 tons	28.42			27.72		
35	4-year rotation Manure 1889–1913 No treatment since 1913	20.58			25.00		
37	4-year rotation Manure 6 tons 1889–1913 Fertilizer since 1913 300 pounds 3–10–4 on corn 200 pounds 3–10–4 on wheat	26.60			25.41		
38	4-year rotation Same treatment as plot 37 but has 2 tons limestone with corn	25.60			22.21		

TABLE 3—*Continued*

PLOT	TREATMENT	SOIL MOISTURE					
		April 11, 1923	July 31, 1923	April 25, 1924	July 31, 1924	April 8, 1925	May 6, 1925
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
39	4-year rotation No treatment	27.10			19.93		
25	3-year rotation Manure 6 tons annually					28.75	24.30
26	3-year rotation Manure 9 tons on corn					29.65	26.35
27	3-year rotation No soil treatment					25.40	24.80
28	3-year rotation Manure 6 tons 1889–1913 No treatment since 1913					27.55	25.80

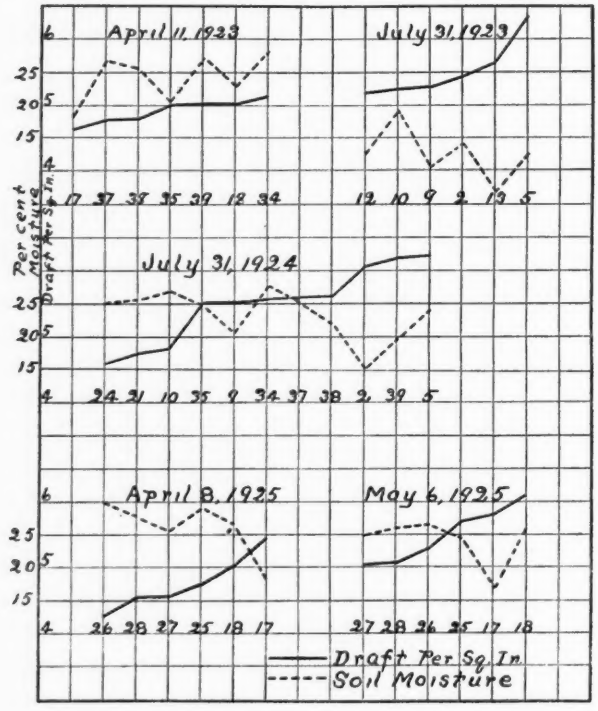

FIG. 2. RELATION BETWEEN THE PER CENT OF SOIL MOISTURE AND THE DRAFT OF PLOWS
Results on each date tests were made

was a calcareous clay contained 11 to 17 per cent of moisture, depending upon the physical character of the soil. The traction increased with decrease of moisture in the soil as follows:

MOISTURE	DRAFT PER SQUARE DECIMETER
per cent	*kgm.*
15.4	47.4
11.1	46.1
5.1	70.7
3.8	78.2

Daviess (1) found that plowing a clover sod with 25.4 per cent moisture gave an average draft of 4.6 pounds per square inch of furrow slice. Similar land after drying down to 19.5 per cent moisture gave an average draft of 5.9 pounds. In this one trial a decrease of 5.9 per cent in moisture increased the draft 28 per cent. Measurements at higher or lower moisture contents were not made.

Ocock (6) made draft measurements on a soil when it was extremely dry, when it was extremely wet, and later when it was in good plowing condition. His results indicate that the plow pulled hardest in the very dry soil and lightest in the soil in good plow condition. The results from the extremely wet soil were slightly higher than for the soil with proper moisture conditions. He made no comparisons of the draft within the range of moisture content that might be considered satisfactory for good plowing.

The results given in this paper differ from Ocock's determinations in that all the measurements were made under at least fairly satisfactory plowing conditions.

Haines (2) reports results of dynamometer tests from the Rothamsted Station on the Barn Field permanent Mangold plots. On one plot the moisture was 28 per cent and the plowing draft was 40 per cent greater than on the immediately adjacent plot with 22 per cent moisture. This was explained on the basis of laboratory tests by the fact that at 28 per cent moisture the soil had reached a peculiar sticky stage corresponding with maximum friction. Neither the treatments of the two plots nor the causes for the difference in moisture contents were given.

In figure 3 comparisons are made between the moisture contents of the soil and the draft both on the unmanured and on the manured plots. The plots have been arranged in the order of increasing draft, including all tests made on each plot. It will be noted that there is a decided general tendency for the moisture curve to fall as the draft curve rises. There are, however, many individual variations. It must be remembered that these curves are based upon results obtained from plots having widely different cropping systems and that they cover tests made at different times from 1923 to 1925. Because of the differences in compactness at these various times the moisture

curves cannot be expected to show as regular correlation as if the tests all could be made at about the same time, but with varying degrees of moisture.

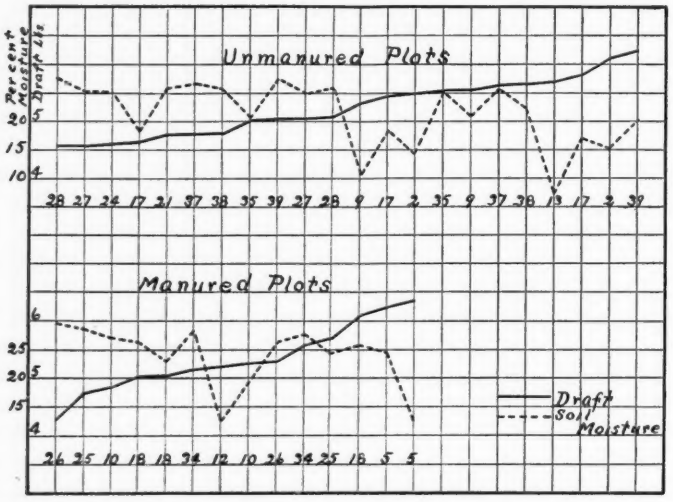

FIG. 3. RELATION BETWEEN SOIL MOISTURE AND THE DRAFT OF PLOWS ON MANURED AND ON UNMANURED LAND

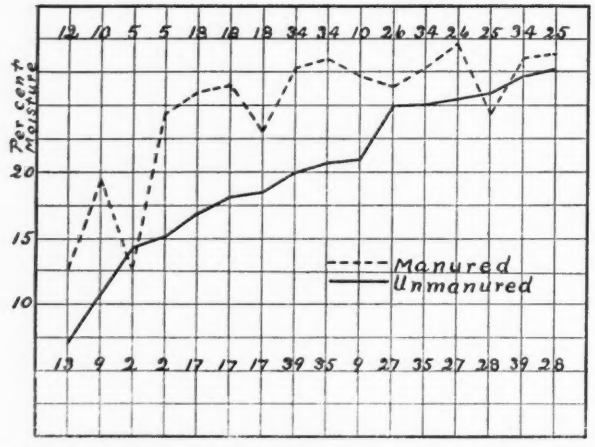

FIG. 4. RELATIVE MOISTURE CONTENTS OF MANURED AND OF UNMANURED PLOTS AT THE VARIOUS SAMPLINGS

EFFECT OF MANURE UPON SOIL MOISTURE

It has long been observed that the water-holding capacity of a soil is increased by applications of organic manures. This fact is brought out in

figure 4 in a comparison of the moisture contents of the manured and unmanured plots at the time of making the dynamometer tests.

Figure 1 shows that on the average and in the greater number of cases, the draft was slightly higher on the manured plots than on the unmanured ones. Figure 3 also shows that the draft tended to decrease as the moisture content of the soil increased. It would seem, if these relations hold true on the average, that if manured land were brought to the same moisture content as the unmanured land the difference in draft would be even greater than is indicated in these tests; that is, the higher moisture content of the manured plots has had a tendency to reduce the draft, but it still remains higher than on the untreated plots.

A comparison of the results from plot 27, untreated, and plot 28 with manure the first 25 years, shows that the draft on April 8, 1925, was practically the same, but that plot 28 had 2.15 per cent more moisture than plot 27. On May 6, plot 28 had a moisture content of 25.8 per cent, or only 0.4 per cent higher than the moisture in plot 27 on April 8. The draft, however, had increased from 4.56 to 5.06 pounds per square inch of furrow slice. This shows that when the moisture content of the manured land was brought down to approximately that of the unmanured, the draft was materially higher. Similar results are shown by a comparison of plots 25 and 26 with plot 27.

From these results it seems likely that if the moisture factor could be eliminated, manured land might be decidedly harder to plow than unmanured land, at least on this particular soil.

SUMMARY

1. Dynamometer tests were made on 19 different plots that had received different rotation and manurial treatments during the past 36 years.

2. The type of soil is Putnam silt loam, but it is somewhat darker and the surface soil is slightly deeper than typical areas of this prairie type.

3. Heavy manuring has had little effect upon the draft of plows, but in general seems to have had a tendency to increase it.

4. The unmanured plots usually work down into a more friable seedbed condition than do the manured plots.

5. Chemical fertilizers, even with rather heavy applications, have not increased the plow draft and, from the limited number of tests, seem to give slightly lower results than manured land.

6. The draft tended to increase as the soil moisture decreased, where the measurements were made under fairly satisfactory plowing conditions.

7. The manured land contained more soil moisture than unmanured land. This fact may have brought the results from the manured and unmanured plots nearer together than if these plots could have been plowed at the same moisture content.

8. It should be understood in this connection that the crop yields from the manured plots have been much higher than from the unmanured land.

REFERENCES

(1) DAVIES, W. M. 1924 A preliminary investigation into the draft of the plough. *Jour. Agr. Sci.* 14: 370–406.

(2) HAINES, W. B. 1925 Studies on the physical properties of soils. *Jour. Agr. Sci.* 15: 178–200.

(3) KÜHNE, G. 1914 Experiments on the draft of a model plow under different working conditions and their practical application. Inaug. Diss. Univ. Giessen. [Also in *Exp. Sta. Rec.* 35: 494.]

(4) MILLER, M. F., AND HUDELSON, R. R. 1921 Thirty years of field experiments with crop rotation, manure, and fertilizers. Mo. Agr. Exp. Sta. Bul. 182.

(5) NOLL, C. F. 1916 Effect of fertilizers on soil structure as indicated by the draft of a plow. Reprint from *Pa. Agr. Exp. Sta. Rpt.* 1913–14: 36–46.

(6) OCOCK, C. A. 1912 The draft of plows. *Trans. Amer. Soc. Agr. Engin.* 6: 13–30.

(7) RINGELMANN, M. 1918 Cultivation and soil moisture. *Compt. Rend. Acad. Agr. France* 4: 746–748. [Abs. in *Rev. Sci.* (Paris) 57: 280–281.]

(8) RUSSELL, E. J., AND KEEN, B. A. 1921 The effect of chalk on the cultivation of heavy land. *Jour. Min. Agr.* (*Gt. Brit.*) 28: 419–422.

ION EXCHANGE IN RELATION TO SOIL ACIDITY[1]

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Received for publication, November 10, 1925

The extensive studies that have been made on base exchange by workers in various countries have contributed to a better understanding of soil acidity. As is well known, a neutral soil when treated with a neutral salt solution, such as KCl, loses a part of its bases (chiefly Ca) and gains an equivalent amount of base from the solution. Dilute acids react with soils in a similar way. If a neutral, carbonate-free soil is treated with a dilute acid, the complex with which salts exchange their bases is attacked, and if the acid is sufficiently dilute the reaction is limited to a substitution of H ions for soil bases (5). Ramann (18) and others have aptly designated acid soils as being unsaturated with respect to base.

A detailed review of the voluminous literature on ion exchange in soils seems unnecessary at this time. Numerous papers have been published on various phases of the subject by prominent workers in Germany, Holland, Russia, England and Japan. After the principal part of the experimental work which is presented herein had been completed, the attention of the authors was called to a very interesting discussion by van der Spek published in the Dutch language (22). In his paper[2] Dr. van der Spek has presented considerable experimental data which, when considered in conjunction with the investigations of Hissink (11), Kappen (14), Ramann (18), Daikuhara (7) and others, have led the author to conclusions quite similar to those drawn independently by Gedroiz (9, 10) and which are in close agreement with the views recently published by Hissink (12), Page and Williams (17), and Robinson and Williams (19) and with those presented in this paper.

As shown by Gedroiz (9) and Hissink (11), ion exchange in soils is subject to the principles of mass action and chemical equilibrium, but the several cations differ considerably in their replacing activity. The available evidence is that the replacing activities of these ions stand in the order $H > Ca > Mg > K = NH_4 > Na$, H ions being much more active than any of the bases named. As bearing on this point the authors have found that upon treating a neutral soil with an acid solution of *N* NaCl (pH 4.0) the cation exchange was effected mainly by H ions and not by Na ions, notwithstanding the great preponderance of Na over H ions in the solution.

The exchange of H ions for soil bases may be effected to a considerable extent by leaching the soil with a solution low in H-ion concentration, such as an aqueous solution of CO_2. We have found for instance that the exchangeable

[1] Paper No. 137, University of California, Graduate School of Tropical Agriculture and Citrus Experiment Station, Riverside, California.

[2] Acknowledgement is due Dr. Richard Bradfield for the loan of an English translation of this paper. The translation was made by Mr. R. V. Allison of New Jersey.

Ca of a sample of neutral Ramona clay loam was reduced from 0.436 per cent to 0.384 per cent by brief extraction with distilled water saturated with CO_2, and to 0.391 per cent by similar extraction with 0.008 *N* acetic acid. The carbonic acid dissolved 0.051 per cent Ca and the acetic acid dissolved 0.042 per cent, which was approximately equal in each case to the observed reduction in the exchangeable Ca. The acidity of the soil as determined by the hydrogen electrode was increased from pH 6.95 to approximately pH 5.0. A second extraction with carbonic acid of the first sample dissolved 0.024 per cent Ca, a third, 0.013 per cent; and a fourth, 0.012 per cent, making a total of 0.1 per cent Ca removed by the four extractions. After the fourth extraction with carbonic acid the soil was found to contain only 0.342 per cent replaceable Ca, which indicates that the acid continued to react chiefly with the exchange complex. However, still stronger acids, such as dilute HCl (0.01 *N* to 0.02 *N*) may also attack constituents other than the exchange complex, as was shown previously (15).

There is little room for doubt that the acids formed in natural soils by biological processes ultimately bring about a substitution of H ions for soil bases with the formation of simple salts of these bases. Under equilibrium conditions the exchange can not become complete unless a strongly acidic solution is used, but when the equilibrium is disturbed by leaching or as a result of absorption by growing plants, the exchange of H ions for soil bases may finally approach completion.

THE REVERSIBILITY OF ION EXCHANGE IN SOILS

The exchange reaction is at least partially reversible, that is, H ions may be displaced from the exchange complex by the base of a neutral salt solution. The usefulness of the Hopkins method and other similar ones for the determination of soil acidity depends upon this fact. Cummins and Kelley (6) pointed out in 1923 that an acid soil may be converted into an alkaline soil by treatment first with NaCl and then with distilled water. The authors have made a further study of this point, using several types of acid soils drawn from various parts of America.

Twenty-five grams of soil was first digested over night at 70°C. with 250 cc. of neutral *N* NaCl or $CaCl_2$. The following morning the samples were transferred to a filter and washed at room temperature with fresh portions of the solutions until the leachates came through approximately neutral. The occluded soluble salts were then removed by leaching with distilled water. The pH values of the soil before and after the treatment are shown in table 1. It will be noted that this treatment brought about a material reduction in the H-ion concentration of every soil studied. However, since (*a*) H ions have a greater affinity for the exchange complex than have metallic ions and (*b*) certain organic acids, the base of whose salts is replaceable, appear to be not readily convertible into salts by treatment with a neutral salt of Ca or Na, it may not be possible to displace all of the H ions by this kind of treatment.

As bearing on this point, a part of the replaceable bases of a neutral soil was first substituted by H ions by treating the soil with a dilute solution of acetic acid, and then an attempt was made to reverse the process by leaching the soil at room temperature with *N* $CaCl_2$. The experiment was only partially successful. The treatment with $CaCl_2$ reduced the H-ion concentration of the acid-treated soil from pH 4.26 to pH 5.42. After the treatment with acetic acid the soil contained a total quantity of replaceable bases equivalent to 0.414 per cent Ca and the final treatment with $CaCl_2$ raised this figure to only 0.455 per cent, instead of to 0.546 per cent, the total amount of replaceable bases expressed as Ca originally present in this soil.

Hissink (12) has obtained similar results. In discussing this point he presents the matter very clearly as follows:

> When we treat a soil with a solution of potassium chloride the filtrate contains H ions. The following reaction takes place:
> Soil H′ (solid phases) + K′ + Cl′ (solution) $\rightleftarrows$ Soil K′ (solid phase) + H′ + Cl′ (solution).
> Thus there is not only an exchange of Ca, Mg and Na ions of the soil for K ions from the KCl solution, but also an exchange of H ions of the soil for K ions from the KCl solution. It should be noted that the solid phase, the soil, becomes less unsaturated, that is less acid, through this process.
> We find, however, that only a part of these H ions is exchangeable. I have for instance leached out a soil (pH 4.5) with a KCl solution up to 2 liters as a result of which the pH of the soil rose to about 5.

On the other hand, Gedroiz (10) seems to think that by leaching the soil with a solution of a neutral salt of high replacing activity, such as $BaCl_2$, the replacement of H ions by Ba may be taken to completion.

By referring to table 1, it will be seen that the leaching with the salt solutions produced a greater reduction in the H-ion concentration of certain acid soils than of others. It seems probable from the evidence at hand, either that soils contain a series of compounds, variable from soil to soil, some of which undergo ion exchange more readily than others, particularly as regards the H ion, or else that the exchangeable ion may occupy more than one position in the molecule of the reacting substance.

The alkalinity developed by treating certain of these soils with NaCl was due to hydrolysis of the Na complexes formed as a result of the substitution of Na for other cations (Ca and H, chiefly the former), and should not be interpreted to mean that all the H was displaced from the exchange complex by Na. In support of this statement Samuels[3] has found in his studies on alkali soils that when Na is the chief replaceable base present the soil may remain alkaline after H ions have displaced a considerable part of the replaceable Na. It appears that the pronounced hydrolytic tendency of the Na complex is responsible for this fact.

The foregoing results help to explain the fact that the application of $NaNO_3$ as

[3] Unpublished thesis.

a fertilizer tends to reduce the acidity of acid soils and if continued may ultimately make the soil alkaline. Moreover, the increased acidity that has been reported from the protracted use of $(NH_4)_2SO_4$ is also readily explained. When this latter salt is applied Ca is at first displaced by NH_4 with the resulting formation of $CaSO_4$. The intervention of nitrification leads to the conversion of NH_4 into HNO_3 with the resulting introduction of H ions into the exchange complex and a consequent increase in the acidity of the soil.

THE DIALYSIS OF SOILS

A neutral soil may be made acidic by merely subjecting it to the process of dialysis, and the change from neutrality to acidity may be hastened by conducting the dialysis under the influence of an electric current. As a means of studying this phase of the subject, an ordinary battery cell, such as is used in

TABLE 1

H-ion concentration of soils as affected by leaching with normal $CaCl_2$ or NaCl followed by leaching with water

SOIL TYPE	LOCATION	pH VALUES		
		Original soil	After treatment with $CaCl_2$	After treatment with NaCl
Clermont silt loam	Indiana	5.14	6.65	7.17
Melbourne clay loam	Oregon	4.99	5.47	6.49
Greenville clay loam	South Carolina	4.80	6.06	6.49
Volusia silt loam	New York	5.22	5.50	7.84
Greenville sandy loam	Alabama	5.10	6.00	
Holston silt loam	Alabama	4.97	6.00	
Rhonerville clay loam	California	5.05	6.51	
Tidal marsh (surface)	California	5.73	6.40	7.81
Tidal marsh (subsoil)	California	4.76	5.51	7.04

automobiles, was separated into three compartments by means of parchment paper held in place by soft rubber.[4] A 25-gm. sample of soil was placed in the central compartment of the cell and all of the compartments were filled to the same level with distilled water. Platinum electrodes connected with a 60- to 65-volt direct current were dipped beneath the surface of the water in the two outer compartments.

The distilled water that was placed in the cathode compartment soon became alkaline whereas that in the anode compartment became slightly acidic. Analysis showed that the alkalinity of the former was due to the hydroxides of bases (chiefly Ca) which dialyzed out of the soil, whereas the acidity noted was due to phosphoric acid, but the amount was always small in comparison with the amount of base found in the cathode compartment.

[4] The authors wish to acknowledge in this connection the helpful suggestions of Dr. S. E. Mattson of the Bureau of Soils. The apparatus used was patterned after that which he has employed in the study of soil colloids.

After having been subjected to the conditions of electro-dialysis for a period of 5 days the soil, whose original pH was 6.95, had become decidedly acidic (pH 4.50). A determination of the replaceable bases showed that the exchangeable Ca had been reduced by the dialysis from 0.436 per cent to 0.280 per cent.

Neglecting the various constituents that are not involved in ion exchange, the following seems a reasonable explanation of the foregoing results: In the presence of water the exchange complex (Ca_xR) ionizes to a slight extent, giving rise to a relatively low concentration of cations (chiefly Ca^{++}) and complex alumino-silicate particles bearing a negative charge. Although a given particle may possibly contain many atoms of exchangeable base, the particle will bear a negative charge whenever the slightest ionization takes place; it will then become essentially a complex anion.

The cation dissociation product of the exchange compounds (Ca^{++}) was able to pass through the parchment membrane and therefore migrated under the influence of the electric current toward the negative pole. H ions, formed by the dissociation of water, also migrated in the same direction. Upon reaching the negative pole the latter were discharged and converted into H_2. The anion, that is, the exchange complex bearing a negative charge, was too large to pass through the membrane. The OH ions of water served, however, to complete the circuit, and upon reaching the positive pole were discharged with the liberation of O_2 and the formation of water. The result was that $Ca(OH)_2$ accumulated in the cathode compartment and the exchange complex remained in the central compartment where it combined with H ions of water and consequently became acidic (base unsaturated). The electric current, therefore, brought about a separation of the products of ionization and thus promoted the ionization process. It merely effected a transfer of ions that were present in the system.

Since, as will be more fully discussed later, the rate at which base is removed from a given soil by dialysis, and probably the rate of cataphoresis of the soil particles also, depend upon the nature of the specific ions present in replaceable form, it appears probable that the degree of ionization of the exchange complex is different depending upon the base with which it is combined.

When H ions are substituted for metallic ions, one of the ionization products of the exchange complex is the H ion. If an aqueous suspension of a partially unsaturated soil is placed in an electric field, H ions together with other diffusible cations that are present will migrate toward the negative pole, but the necessary discharge of the soil complex bearing the negative charge demands that H ions must again be taken up from the solution. Thus the exchange complex, only partially saturated with base and therefore acidic at the outset, will become still more so as the dialysis proceeds.

It seems probable that the process involved in the electro-dialysis of a soil is similar in principle to that which obtains in the region of plant roots where bases are being actively absorbed. In the latter case the valency of the

exchange complex remains saturated through the taking up of H ions from the soil solution. The H ions, being formed by CO_2 excretion and by microbiological activity, replace the bases, and the absorption of the bases by plant roots disturbs the equilibrium by taking up one of the products of the exchange reactions. The result is that in the course of time the soil becomes acidic.

As has been shown by various workers in the field of colloid chemistry, ions condensed on the surface of colloidal materials may be displaced by other ions of like charge. In accordance with the view of a certain school of colloid workers it has long been customary in agricultural literature to explain the phenomena of soil acidity and base exchange on the basis of adsorption. On the other hand, the chemical substitution of one base for another, or of H for base, in the natural silicates appears to be an established geological and mineralogical fact. So far as we are aware every critical study that has been made on the various reactions with soil materials has yielded results that are harmonizable with accepted chemical principles. For example, it has often been reported that different alkalies do not combine with acid soils in chemically equivalent quantities, but Truog (21) pointed out several years ago that, if the determination is so made as to avoid side reactions, the law of combining weights really applies to this reaction. More recently Bradfield (1) in connection with his interesting work on soil colloids has shown that when the experimental conditions demanded by the principles of physical chemistry are maintained the neutralization of the colloid by means of different alkalies follows accepted chemical principles. As is pointed out by Bradfield the results are in harmony with the view that the acidity is due to true acid compounds of low solubility and low ionization. Unpublished data obtained in this laboratory have further strengthened the chemical interpretation of ion exchange in soils.

The aforementioned and various other experiments suggest that ion exchange in soils involves true chemical compounds. The active substances are probably colloidal and therefore the reactions take place largely at the interfaces between the particles and the solution, but this does not prevent its being chemical. It is true that electro-magnetic forces may possibly bring about an orientation of ions and molecules at the interface between a solid and a solution somewhat different from that which obtains in other parts of the solution and which may affect the electro-kinetic properties of the particles. However, as Truog (21) has pointed out, the reactions with the exchange constituents of soils appear to be strictly chemical. The so-called adsorption compounds of soils are probably true chemical compounds.

Hissink (12) recently stated:

> The opinion has of late been gaining more and more ground that the cause of the adsorption is to be sought in chemical attraction; in other words a chemical compound is formed by the adsorbed bases and the particles of the soil. These soil particles can only be the acids in the clay and in the humus, briefly the clay acids and the humus acids. With regard to the composition of these hypothetical clay acids we can only say that they must be a kind of alumino-silicic acid; the humus acids are of course organic acids.

In a recent discussion of the literature Drummond and Page (8) state:

> Now that Bradfield (2, 3) has clearly demonstrated that the colloidal clay material of soils does actually behave as a true acid, this fact together with the proof that the humic acids of soils are also true acids provides a sound experimental basis for Hissink's hypothesis and it is possible to explain all the phenomena in question as chemical ionic reactions of weak acids (clay acids and humic acids), these reactions being localized at a solid-liquid interface owing to the fact that these acids are insoluble and present in the soil as colloidal particles or as gel on the surface of mineral soil particles.

Robinson and Williams (19) have expressed a similar opinion.

The existing experimental data seem to agree with the assumption that the inorganic exchange complex is composed of a complex salt of one and probably more of the polybasic alumino-silicic or silicic acids.[5] When the bases have been substituted by H ions the compounds become acid silicates. The soil then manifests acid properties.

THE RELATION OF TRIVALENT BASES TO ION EXCHANGE

When an acid soil is treated with a neutral salt solution, such as KCl or NH_4Cl, more or less Al, Fe and Mn usually pass into the solution. We have shown (15) that the sum of all the bases which are displaced from the soil, including the trivalent metals, may be approximately equivalent to the amount of base which is absorbed from the salt solution. Various investigators (7, 14, 16) have found that the titratable acidity of an extract, obtained by treating an acid soil with a neutral salt solution, is approximately equal to the Al content of the extract. These facts suggest that acid soils may contain trivalent bases in replaceable form. The following experiments were made in the hope of throwing some light on this point.

Different portions of a neutral soil were leached first with solutions of $AlCl_3$ of various strengths and then with distilled water until free from Cl. The chief base removed from the soil by this treatment was Ca and the amount removed increased with the concentration of the $AlCl_3$ solution. The pH of the soil was then determined with the hydrogen electrode and the replaceable bases were determined by the use of a neutral solution of *N* NH_4Cl.

The results recorded in table 2 show: (*a*) that the preliminary treatment with $AlCl_3$ made the soil distinctly acid, and (*b*) that as the strength of $AlCl_3$ was increased the content of bases (chiefly Ca) originally present in replaceable form suffered progressive diminution. The data suggest, however, that the bases were replaced not by Al ions but by H ions formed as a result of the hydrolysis of $AlCl_3$. It will be noted, for instance, that the amount of NH_4

[5] As pointed out by Gedroiz (9), Hissink (11), and others soils usually contain more or less of organic substances (humic bodies), as well as inorganic substances, which take part in ion exchange. With highly organic soils, such as peaty soils, the chief part of the exchange is probably borne by organic bodies. The soils with which we have worked, however, contain very small amounts of organic matter.

absorbed from the NH_4Cl solution, which is an accurate measure of cations displaced by NH_4Cl, was always in stoichiometric excess of the sum of the displaced monovalent and divalent bases, this being especially pronounced when the higher concentrations of $AlCl_3$ were used. Moreover the NH_4 absorbed was not stoichiometric with the bases dissolved even assuming that the Al found in certain cases was really brought into solution by exchange. As a matter of fact the treatment with concentrations of $AlCl_3$ ranging from 0.001 *N* to 0.01 *N* brought about a progressive increase in the acidity of the soil and a corresponding diminution in the replaceable bases without the soil having acquired any substantial amount of replaceable Al.

Since solutions of $AlCl_3$ hydrolyze into HCl and $Al(OH)_3$, the former being highly ionized and the latter only slightly so, the concentration of H ions in the dilute solutions of $AlCl_3$ must have exceeded that of Al ions. The soil bases were displaced by the H ions just as if the soil had been treated with a pure acid of low ionization. At the same time more or less Al was absorbed

TABLE 2

Effects of extraction with NH_4Cl after first treating the soil with $AlCl_3$

NORMALITY OF $AlCl_3$	pH OF SOIL AFTER $AlCl_3$ TREATMENT	BASES EXTRACTED (PER CENT OF SOIL)			MILLIGRAM EQUIVALENTS	
		Ca	Mg	Al	Bases replaced exclusive of Al	NH_4 absorbed
0	6.95	0.436	0.073	0	27.9	27.3
N/1000	5.96	0.359	0.065	0	23.3	27.2
N/500	5.65	0.338	0.046	0	20.7	27.2
N/250	5.05	0.301	0.048	0	19.0	26.1
N/100	4.94	0.202	0.033	Trace	12.8	26.5
N/50	4.84	0.089	0.021	0.117	6.2	25.1
N/10	4.84	0.036	0.013	0.197	2.9	20.7

by the soil as was indicated by the diminished Al content of the solutions used in treating the soil. This absorption, however, was probably effected through the mutual colloidal precipitation of $Al(OH)_3$ and soil colloids rather than by an exchange of Al ions for soil bases, contrary to the conclusion drawn by Gedroiz (9) from similar experiments on the basis of a determination of the Al content of the soil before and after it was treated with a solution of $AlCl_3$.

The absorption of NH_4 in excess of that required to displace the Ca and Mg, referred to above, was probably due to the exchange of NH_4 ions for H ions in the exchange complex.

It will be noted that the preliminary treatment with the more dilute solutions of $AlCl_3$ brought about an inverse proportionality between the acidity of the soil and its total content of replaceable base, but that this inverse relationship disappeared after approximately one-half of the replaceable bases had been substituted by H ions. In connection with electro-dialysis experiments it was found that upon bringing about approximately complete substitution of H ions for the bases of this soil the acidity finally reached pH 4.0,

which appears to be the maximum acidity attainable by the ionization of the alumino-silicic and organic acids of this soil.

The existing evidence indicates, as pointed out by Saint (20), that it is the solvent power of the salt solution, enhanced by displacement of H ions from the exchange complex, that is chiefly responsible for the solution of the trivalent bases upon treating an acid soil with a neutral salt solution. It is also indicated that in some cases the soil solution itself may become sufficiently acid to dissolve significant amounts of these bases. In this connection we have found that $Al(OH)_3$, either when absorbed from a solution of $AlCl_3$ or when added to a soil as such, is considerably more soluble in an acid solution of KCl than in an NH_4Cl solution of equal H-ion concentration.

As has been shown by various workers, Al is the principal trivalent base of importance in certain acid soils. In other soils Mn predominates. We have found, for instance, that with a sample of neutral Ramona clay loam the solubility of Mn in *N* NH_4Cl was increased from a trace to 0.034 per cent by dialyzing out approximately one-third of the replaceable bases, and to 0.066 per cent by dialyzing out approximately two-thirds of the bases. The dialysis produced no change in the solubility of Al and Fe. In addition a sample of Greenville sandy loam, sent from Alabama by Dr. F. W. Parker, contains 0.037 per cent Mn soluble in *N* NH_4Cl, and a sample of Holston silt loam contains 0.081 per cent, but neither of these acid soils contains appreciable amounts of soluble Al or Fe. On the other hand a sample of colloidal material (pH 5.35) separated by Dr. Bradfield from acid Putnam clay was found to contain 0.145 per cent Al and 0.112 per cent Fe soluble in *N* NH_4Cl.

Whatever may be the origin of the compounds of the trivalent bases and the mechanism by which they are brought into solution in acid soils, either by salt solutions or by the soil solution, it is clear that soil acidity is a phenomenon which involves a diminution in the supply of replaceable Ca with a corresponding increase in the H content of the exchange complex. Acid soils are, therefore, to be regarded as being in a state of unsaturation with respect to bases.

THE CONTENT OF REPLACEABLE CA IN ACID SOILS

A determination of the replaceable Ca in several acid soils obtained from various parts of America showed a relatively low content of Ca. The results are in agreement with those obtained by Robinson and Williams from a study of Welsh soils (19). The deficiency in the replaceable Ca becomes especially apparent when the data (table 3) are compared with those previously reported for approximately neutral soils both in America (15) and in Europe (9, 11, 17).

It does not follow, however, that an acid soil *necessarily* contains a low absolute amount of replaceable Ca, for the substitution of H ions for only a comparatively small part of the replaceable Ca may produce an acid reaction, as was shown earlier in this paper. Neither does it follow that the exchangeable H-ion content is necessarily high in an acid soil whose replaceable Ca is low, since the total content of exchangeable cations, as well as that of Ca, may

be low. These statements are strongly supported by unpublished data obtained in the course of studies on the colloidal materials which were separated from different soils by the use of the super-centrifuge.

GENERAL DISCUSSION

At least three general principles must be considered in arriving at an understanding of soil reaction; namely, (*a*) direct ionization, (*b*) hydrolysis, (*c*) the so-called buffer effect.

As is shown by the foregoing experiments on dialysis, the exchange complex ionizes to some extent. If Ca is the only cation component of this complex, the compounds are reasonably stable chemically and practically non-hydrolizable and, therefore, give an approximately neutral ionization. When H ions enter, the compound tends to give an acid ionization, but there is some doubt as to

TABLE 3

Replaceable Ca content of various acid soils

TYPE	LOCATION	pH	Ca
			per cent
Clermont silt loam	Indiana	5.14	0.068
Unclassified clay loam	California	4.97	0.027
Rhonerville clay loam	California	5.05	0.053
Hagerstown clay loam	Pennsylvania	4.77	0.021
Melbourne clay loam	Oregon	4.99	0.037
Greenville clay loam	South Carolina	4.80	0.060
Volusia silt loam	New York	5.22	0.103
Cecil clay loam	Georgia	6.12	0.018
Tidal marsh clay loam	California	5.73	0.112
Tidal marsh subsoil	California	4.76	0.088
Greenville sandy loam	Alabama	5.10	0.041
Holston silt loam	Alabama	4.97	0.056
Miami loam	Michigan	6.59	0.219
Glaucester silt loam	Wisconsin	5.90	0.169

whether the soil with a small part of the exchangeable base substituted by H ions is necessarily acidic. Gedroiz (9, 10) has suggested, for example, that, although $CaCO_3$ serves to protect the exchange complex against attack it is possible that the substitution of H ions of biological origin for bases may begin before the last traces of $CaCO_3$ have been decomposed. If this is true it means that the base-unsaturated complex can exist in equilibrium with $CaCO_3$.

It seems possible as suggested by Page and Williams (17) that:

> As weak acids these complex acids will exist entirely in the form of salts (i.e. the soil will be saturated in the modern sense) only when the solution is quite alkaline, with a pH far above 7, whereas in a neutral or faintly alkaline soil, with a pH of 7 to 8, in equilibrium with calcium carbonate, which in Ramann's terminology would be termed an absorptively saturated soil, the degree of saturation in the modern sense would still be far from complete; that is an appreciable proportion of the complex acids would still exist in the free state, or the

absorbing complex would still contain exchangeable hydrogen ions which could be liberated by base exchange with a neutral salt.

If this view is sound, it follows that the mere application of an excess of $CaCO_3$ will not change an acid soil into a state of base saturation (17, p. 583). The application of $CaCO_3$ would, of course, modify the reaction of the soil and improve its crop-producing power, as experience has abundantly proved. Hissink (12) recently published data which indicate that an acid reaction may not ensue until a relatively large percentage of the base of a saturated soil has been substituted by H ions.

We expect to discuss this point more fully in a separate paper to be devoted to a consideration of analytical methods for the determination of replaceable H ions. At present it will suffice to say that our results indicate that, so far as the exchange complex of normal soils is concerned, an acid reaction ensues whenever any considerable part of the replaceable base is substituted by H ions. It should be borne in mind, however, that the exchange silicates, like the phosphates, may ionize in various ways. The ionization might be represented by either of the following:

$$HR \rightleftarrows H^+ + \bar{R},$$

$$Ca_xHR \rightleftarrows H^+ + Ca_x\bar{R} \qquad \text{or}$$

$$Ca_xHR \rightleftarrows Ca^{++} + Ca_{(x-1)}HR.$$

If the last predominates the reaction would probably be approximately neutral.

Hydrolysis may involve both the exchange complex and the various crystalline minerals of soils. When Na comprises any considerable part of the total replaceable bases, the complex, as already pointed out, tends to undergo hydrolysis with the resulting formation of small amounts of NaOH.[6] The crystalline silicates, as well as $CaCO_3$, may also undergo hydrolysis. As is well known, various silicates, such as the feldspars, yield alkaline solutions by hydrolysis. The hydrolytic products of these silicates may possibly dominate the reaction of a carbonate-free soil whose exchange complex is slightly unsaturated with bases.

The buffer effect of soils, as commonly understood, is concerned mainly with the exchange complex and is an expression of the replacing activity of H ions. As is indicated above, H ions are energetic replacing ions. When the H-ion concentration of a solution brought into contact with a given soil exceeds that given by the ionization of the exchange complex, an exchange of ions will take place with the result that H ions will be absorbed from the solution and a simple salt of the substituted base will be formed. The buffer property against acids is thus conditioned on the presence of base in replaceable form and its extent is determined by the amount present.

[6] This hydrolysis, as suggested by Gedroiz (10) and by Joffe and McLean (13), may, of course, be regarded as merely an aspect of ion exchange in that H ions of water displace Na from the soil. It is doubtful, however, whether anything is gained by this view.

From the foregoing discussion it must be apparent that the H-ion concentration of a soil is not necessarily correlated with the composition of the soil solution. On the other hand the composition of this solution, its constancy, and its rate of renewal vitally affect the crop-producing power of the soil. Reasoning from general principles one must assume that the composition of the soil solution is profoundly influenced by biological action and that the bases required by plants are brought into solution largely by biologically formed acids. Recent investigations by Burd (4) strongly support this view. Since in the absence of carbonates these acids tend to react, as already shown, by the substitution of H ions for Ca, a soil which is free from $CaCO_3$ and low in replaceable Ca must be regarded as being essentially deficient in Ca. Acids formed in such a soil by biological action tend to bring into solution toxic concentrations of Al or Mn.

From this point of view the unproductivity of acid soils and the beneficial effects of liming become intelligible. As pointed out by Robinson and Williams (19) the unproductivity is not necessarily due to the H-ion concentration directly; toxic concentrations of Al or Mn and insufficiency of phosphate supply may be involved, and perhaps equally important may be the inadequacy of the available Ca supply. The application of lime tends to reduce the H-ion concentration, lower the solubility of Al, and furnish an available supply of Ca. In consequence of all these changes together with the indirect effect on the solubility of phosphates and on micro-biological processes, crop growth is promoted.

These studies also afford an explanation of the well-known fact that, whereas the application of $CaCO_3$ may improve the crop-producing power of an acid soil, the application of gypsum may not do so. The latter would undoubtedly tend to overcome the deficiency in available Ca but this advantage might be more than offset by the replacement of H ions with the consequent increase in the acidity of the soil solution and the resultant dissolving of toxic Al.

SUMMARY

1. Dilute acids react with soils in much the same way as neutral salts. The reaction involves an exchange of ions. When reacted upon by acids the exchange complex gives up base in exchange for H ions. The soil then becomes unsaturated with base and therefore acidic. The condition of unsaturation with respect to base is characteristic of acid soils. This condition is brought about in natural soils by the combined effect of biologically formed acids, leaching and the absorption of bases by growing plants.

2. H ions are energetic replacing ions. Weak acids, such as carbonic acid, are capable of effecting an exchange of H ions for soil bases. The H ions may in turn be displaced from the soil, in part at least, by the base of a neutral salt, with the resulting formation of an acid solution.

3. The exchange complex ionizes to some extent, as dialysis experiments indicate. The ionization products of a base-saturated soil are composed

largely of the replaceable bases as cations and the alumino-silicate particles as anions. When the dialysis is conducted under the influence of an electric current, the bases accumulate around the cathode and can be separated from the soil and determined as the hydroxides. At the same time the exchange complex becomes acidic through the taking up of H ions from the solution. It is possible to effect approximately complete substitution of H ions for the replaceable bases by this means.

4. The replaceable bases of mineral soils are believed to be chemically combined as salts of one or more of the alumino-silicic acids, and when substituted by H ions the compounds become acid silicates. It is suggested that the electro-negative character of soils, their cataphoretic property, etc., are due in part at least to the ionization of true chemical compounds, rather than to the influence of adsorbed ions.

5. When a soil is treated with $AlCl_3$ a replacement of soil bases takes place. The H ion, formed as a result of hydrolysis, and not the Al ion, is responsible for the resplacement. The trivalent bases which are removed from an acid soil by extraction with a neutral salt solution are probably brought into solution as a result of the solvent power of the solution, which power is materially increased by the H ions that are displaced from the exchange complex by the neutral salt.

6. A considerable number of acid soils were found to contain subnormal amounts of replaceable Ca. It seems probable that this condition will prove to be a general characteristic of acid soils.

7. The H-ion concentration of a soil is determined by: (*a*) the dissociation products of the exchange complex which it contains, (*b*) the hydrolytic products of the exchange compounds and various other compounds that may be present, and (*c*) the buffer property of the soil. The last-named factor is determined largely by the total amount and by the specific nature of the several replaceable bases present.

8. The application of lime produces various chemical effects on acid soils. Among the more important are: (*a*) the neutralization of acids with the consequent introduction of Ca into the exchange complex, (*b*) a reduction in the solubility of Al, and (*c*) an increase in available Ca. Acid soils are physiologically deficient in base; their available Ca is likely to be inadequate.

9. An explanation is offered for the fact that the application of $NaNO_3$ tends to reduce the acidity of soils, whereas $(NH_4)_2SO_4$ increases it. The superiority of $CaCO_3$ over $CaSO_4$ as a treatment for acid soils is briefly referred to.

10. The results reported in this paper are in harmony with the conclusions of Truog, Bradfield and several European investigators; namely, that the acidity of mineral soils is due primarily to acid silicates.

REFERENCES

(1) BRADFIELD, RICHARD 1923 The nature of the acidity of the colloidal clay of acid soils. *In* Jour. Amer. Chem. Soc., v. 45, p. 2669–2678.

(2) BRADFIELD, RICHARD 1924 The importance of hydrogen-ion concentration control in physico-chemical studies of heavy soils. *In* Soil Sci., v. 17, p. 411–422.

(3) BRADFIELD, RICHARD 1924 The effect of the concentration of colloidal clay upon its hydrogen-ion concentration. *In* Jour. Phys. Chem., v. 28, p. 170–175.

(4) BURD, J. S. 1925 Relation of biological processes to cation concentration in soils. *In* Soil Sci., v. 20, p. 269–283.

(5) COMBER, N. M. 1925 The rôle of the electronegative ions in the reactions between soils and electrolytes. *In* Trans. Faraday Soc., v. 20, p. 567–572.

(6) CUMMINS, ARTHUR B., AND KELLEY, WALTER P. 1923 The formation of sodium carbonate in soils. Cal. Agr. Exp. Sta. Tech. Paper 3.

(7) DAIKUHARA, G. 1914 Acid mineral soils. Imp. Cent. Agr. Exp. Sta. Japan Bul. 2.

(8) DRUMMOND, J. C., AND PAGE, H. J. 1924 The chemical interpretation of the phenomenon of adsorption and acidity in soils. *In* Ann. Rpts. Prog. Chem. (Chem. Soc., London), v. 21, p. 178–182.

(9) GEDROIZ, K. K. 1916 The absorbing capacity of the soil and soil zeolitic bases (Russian). *In* Zhur. Opit. Agron., v. 17, p. 472–527.

(10) GEDROIZ, K. K. 1924 Soils unsaturated with bases. Method of determining in soils the hydrogen present in an absorbed condition. Soil requirements of lime as a neutralizing agent (Russian). *In* Zhur. Opit. Agron., v. 22, p. 3–27.

(11) HISSINK, D. J. 1922 Beitrag zur Kenntnis der Adsorptionvorgänge im Boden. Methode zur Bestimmung der austauschfähigen oder adsorptiv gebundenen Basen im Boden und die Bedeutung dieser Basen für die Prozesse, die sich im Boden abspielen. *In* Internatl. Mitt. Bodenk., v. 12, p. 81–172.

(12) HISSINK, D. J. 1925 Base exchange in soils. *In* Trans. Faraday Soc., v. 20, p. 551–566.

(13) JOFFE, J. S., AND MCLEAN, H. C. 1924 Alkali soil investigations: II. Origin of alkali soils; physical effects of treatments. *In* Soil Sci., v. 18, p. 13–30.

(14) KAPPEN, H. 1916 Zu den Ursachen der Azidität der durch Ionenaustausch sauren Böden. *In* Landw. Vers. Sta., v. 89, p. 39–80.

(15) KELLEY, WALTER P., AND BROWN, S. MELVIN 1924 Replaceable bases in soils. Cal. Agr. Exp. Sta. Tech. Paper 15.

(16) LIESEGANG, H. 1921 Weitere Untersuchungen zur Austauschazidität der Mineralböden. *In* Landw. Vers. Sta., v. 99, p. 191–230.

(17) PAGE, H. J., AND WILLIAMS, W. 1925 Studies on base exchange in Rothamsted soils. *In* Trans. Faraday Soc., v. 20, p. 573–585.

(18) RAMANN, E. 1911 Bodenkunde, ed. 3, p. 242. Springer, Berlin.

(19) ROBINSON, G. W., AND WILLIAMS, RICE 1925 Base exchange in relation to the problem of soil acidity. *In* Trans. Faraday Soc., v. 20, p. 586–593.

(20) SAINT, S. J. 1925 The relation between the pH value, the lime requirement and the thiocyanate colour of soils. *In* Trans. Faraday Soc., v. 20, p. 594–598.

(21) TRUOG, E. 1916 The cause and nature of soil acidity with special regard to colloids and adsorption. *In* Jour. Phys. Chem., v. 20, p. 457–484.

(22) VAN DER SPEK, J. 1922 Action of solutions of neutral salts on soils. Contribution to knowledge of soil acidity. *In* Verslag. Landbouwk. Onderzoek, Rijkslandbouwproefsta (Netherlands), v. 27, p. 162–202.

THE EFFECT OF VARYING THE NITROGEN SUPPLY ON THE RATIOS BETWEEN THE TOPS AND ROOTS IN FLAX

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Received for publication November 2, 1925

PART 1

In an earlier paper (1) in which the writer reported studies bearing upon the mechanism of the physiological effects of nitrates in altering the ratio of top growth to root growth in seed plants, it was noted that certain plants showed no appreciable change of top-root growth ratios when the nitrate content of the medium in which they were growing was increased. *Flax* was one of the plants which showed very little or no response to the nitrate treatment, whereas certain other plants such as *barley* and *corn* showed unmistakable increments in the ratios as nitrates were increased.

The writer made the following statement about the behavior of *flax* in the aforementioned paper:

> It will be noticed that this plant makes no appreciable response, in the ratio of tops to roots, to increased nitrate content of the solution. In other words, it would seem that in the case of *flax* we are dealing with a plant of a different physiological constitution in so far as its ability to utilize nitrates is concerned. To what range it might respond, the limits of this experiment have not permitted investigation, but this fact presents a very interesting problem from the standpoint of *flax* nutrition.

Further studies have been carried on with *flax*, to the end of throwing some additional light upon the behavior of this plant.[1] The *flax* plants were grown in quart jars in specially devised nutrient solutions, which were described in the former paper. Though the preparation of these solutions may require somewhat more labor than the nutrient solutions which one finds given ordinarily for physiological studies, they furnish a much better method of varying simple anions or cations, and at the same time they avoid the introduction of non-nutrient constituents. Three sets of plants were grown simultaneously in solutions which differed mainly in nitrate content. The pH value of the low nitrate solution was 6.46; of the medium nitrate, 6.81; and of the high nitrate, 6.46. The flax used was a seed type, variety Winona, C.1, no. 179.[2]

These studies were conducted along two lines. The first effort was concerned with growing the plants, noting growth characters, and with harvesting at

[1] These investigations were carried on in the Biological laboratory of Hampton Institute.

[2] The flax was kindly supplied by Mr. A. C. Dillman in charge of seed flax investigations of the United States Department of Agriculture.

intervals of one week, beginning in the experiments reported here, 32 days after the cultures were set up. Four cultures were harvested to a series, the tops being carefully separated from the roots and both dried to constant weight, at 100°C.

Table 1 gives the result of an experiment of 45 days duration. It will be seen that for the 32-day period the ratios of tops to roots as shown by their dry weights are 3.34, 3.09 and 3.22 respectively for the low nitrate, medium nitrate, and high nitrate solutions; for the 39-day period the results are not materially changed; and the small change for the 45-day period is not significant

TABLE 1

Ratio of top growth to root growth in flax as nitrate concentration is increased

SOLUTIONS	SERIES 1–32 DAYS			SERIES 2–39 DAYS			SERIES 3–45 DAYS		
	Tops	Roots	Tops / Roots	Tops	Roots	Tops / Roots	Tops	Roots	Tops / Roots
	gm.	gm.		gm.	gm.		gm.	gm.	
Solution 1. Low nitrate..	0.8957	0.2675	3.340	1.5935	0.5242	3.039	2.5722	0.7488	3.43
Solution 2. Medium nitrate.....	0.6917	0.2237	3.092	1.1169	0.3682	3.034	2.1732	0.5581	3.89
Solution 3. High nitrate.	0.7183	0.2227	3.220	1.0493	0.3233	3.240	1.6464	0.4134	3.98

TABLE 2

Ratios of top growth to root growth in barley and in corn as nitrate concentration is increased

		28 DAYS	35 DAYS	42 DAYS	49 DAYS
Barley.....	Solution 1	4.37	4.94	4.99	5.33
	Solution 2	5.13	6.56	7.71	8.28
	Solution 3	5.75	6.84	7.66	9.08
		27 DAYS	34 DAYS		41 DAYS
Corn.....	Solution 1	4.44	5.71		6.41
	Solution 2	4.87	7.54		9.75

when compared with *barley* or *corn* grown for the same periods, and under similar conditions. Figures have been given (1) which show closer ratios for flax than are reported here.

Table 2 shows markedly increasing ratios with *barley* and *corn*. Several preliminary experiments were carried on with *flax*, all giving practically the same results.

A comparative study of the figures in tables 1 and 2 shows that the smallest quantity of nitrate used in *flax* has the same effect as the largest in stimulating the growth of tops. It would thus seem that the use of nitrates for *flax* culture, except in minimal quantities would be a waste.

PART 2

It was thought that since *barley* and *flax* as types, showed such different behavior in the presence of increased amounts of nitrates, a chemical analysis for the total nitrogen content of the plants grown with the different treatments of nitrates would throw some light upon the relative assimilation of nitrogen by the two. For this purpose, therefore, a second set of experiments was made.

The material preserved from the first set of experiments (tables 1 and 2)

TABLE 3

Percentages of nitrogen in flax and barley compared when grown in nutrient solutions with different quantities of nitrates

	NITROGEN IN FLAX		NITROGEN IN BARLEY	
	Tops	Roots	Tops	Roots
	per cent	*per cent*	*per cent*	*per cent*
Solution 1. Low nitrate	3.36	2.68	2.40	
	3.14	2.64	2.44	
	3.30			
	3.30			
	Total 13.10	5.32	4.84	
	Mean 3.275	2.66	2.42	
Solution 2. Medium nitrate	3.70	3.34	4.34	3.80
	3.64	3.40	4.30	4.04
	3.78			
	3.88			
	Total 15.00	6.74	8.64	7.84
	Mean 3.75	3.37	4.32	3.92
Solution 3. High nitrate	3.92	3.58	4.74	4.18
	4.38			
	4.02	3.44	4.78	4.24
	4.44			
	Total 16.76	7.02	9.52	8.42
	Mean 4.19	3.51	4.76	4.21

was now ground finely, in separate lots, and carried through the Kjeldahl process for total nitrogen determinations.

Determinations for the tops of *flax* were run in quadruplicates, whereas all others were in duplicates.

Table 3 gives the results of these experiments. The differences among the percentages of nitrogen found in tops of *flax* grown in the three solutions are small, 3.275 per cent, 3.75 per cent, and 4.19 per cent respectively. In case of *barley* the percentage of nitrogen in tops of the low nitrate cultures—2.42

per cent—was decidedly lower than for the medium—4.32 per cent—and high nitrate—4.76 per cent. The small difference in percentage of total nitrogen found in *flax*, paralleled the ratios of top growth to root growth in this plant, which shows slight and rather irregular differences. This is in contrast to the large difference in percentage of nitrogen found between the low and medium nitrate cultures of *barley*, which showed, also, large differences in the ratio of top growth to root growth.

DISCUSSION

In the case of *barley* and *corn* the increased ratio of tops to roots which results from increasing the amount of nitrogen in the solution seems to be due to the increased use of carbohydrates in the tops, because the greater nitrogen supply allows for greater growth. There is no inhibiting effect of nitrates upon the roots, but as the tops are stimulated to use more of the photosynthetic carbohydrates the roots decrease in number and, therefore, show relatively less growth; the result being a marked increase in ratio of tops to roots. The mechanism seems to be different with *flax*. These and former studies show that in this plant the tops are not able to profit by an increased supply of nitrates beyond a certain low limit. They show further that the smallest amount of nitrates used was as effective in bringing about a change in ratio of top growth to root growth as the largest which was twenty times as much.

REFERENCES

(1) TURNER, THOMAS W. 1922 Studies of the mechanism of the physiological effects of mineral salts in altering the ratio of top to root growth in seed plants. *Amer. Jour. Bot.* 8: 415–445.

PHYSIOLOGICAL ACTIVITY OF THE SEMINAL AND NODAL ROOTS OF CROP PLANTS

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Received for publication April 8, 1925

INTRODUCTION

Plants of the grass family possess two distinct root systems which develop at different periods. The primary or seminal root system develops immediately upon germination and usually consists of several roots, the number of which depends on the species of plant. The young seedling is entirely dependent for its nutrition on this primary or "temporary" root system. Later, during the period of tillering, a second root system, known as "nodal" or "permanent" develops from the lower nodes of the main stem and of the tillers. When the grain is planted shallow, or when it germinates in the light, as for instance in the laboratory, both root systems are closely connected, the nodal roots surrounding the seminal ones, so that these latter can scarcely be noticed. When the grain is planted deep, the nodal roots are obviously separated from the seminal ones by the elongated wiry lowest internode (wheat, barley, rye) or by the mesocotyl (mais, sorghum).

The two root systems exhibit great differences in their morphological and anatomical structures. Detailed descriptions of the structure of both root systems may be found in the works of Jackson (3), Percival (8), Sleskin (16), and O. A. Walther (18, 19). Whereas the primary roots are very slender and branched throughout their length, having a thin walled cortex with no exodermis, the nodal roots are centrally thicker, and possess a wider central stele. Wide difference of opinion exists, however, concerning the functions and life activity of the two root systems. There seems to be full agreement among the investigators in this field (2, 4, 6, 7, 9, 10, 11, 13, 15, 21, 22) that the primary root systems (in most of the plants) function only temporarily, and gradually die off when the nodal root systems develop. The question, however, is far from being settled, especially in plants like corn and sorghum. Miller (5), Schellenberg and Kirchner (4), and Zawodny (23) find that the single seminal root of corn and sorghum functions in the plant during all its life. They even suggest that this life-long function of the primary root system distinguishes this group of crops from the rest of the grass family. Percival (8) admits the possibility of the seminal roots functioning throughout the life of the plant, as they are often found undecayed up to the time of harvest. Jackson (3), studying the root system of barley at different stages of development, states that the seminal roots form the "bulk" of the root system of this plant. Rotmistrov (12)

[1] This study was carried out in the Laboratory of Plant Physiology in the Leningrad Agricultural Institute. The writer is deeply indebted to Prof. O. A. Walther for suggesting the problem and for valuable and helpful criticisms in the course of the work.

has observed that the primary roots continue to be the main part of the root system during the entire period of vegetation, the nodal roots developing only when conditions of moisture and nutrition are favorable. Finally Weaver, Jean, and Crist (20) after numerous investigations on the root systems of these plants agree with Rotmistrov, that the seminal roots remain alive and active up to the time of harvest.

In view of these contradictory opinions it appeared necessary to study the functions of the two root systems experimentally; more so because most of the investigators drew their conclusions from mere observations of the appearance of roots, and not from experimental work.

The purpose of these experiments was, therefore, to study the rôle that each of the two root systems plays in the nutrition of the plant.

Two series of experiments were carried out: In the first, wheat, barley, and rye were grown in the culture solution with the two root systems separated, each being immersed in a different jar; in the second, one of the two root systems was entirely removed from the plant in order to observe how the plants would react to the removal of either of the root systems.

EXPERIMENTS WITH ISOLATED ROOT SYSTEMS

Methods

Seeds of pure line of wheat (*Tr. vulgare lutescens*), summer and winter rye (*Secale cereale*), as well as barley for the second series of experiments (*Hordeum v. pallidum mandschuricum*, no. 69) were obtained from the Station of Applied Botany and Selection in Leningrad. Seeds of bare barley were obtained from the Nikolaewski Experiment Station of the Leningrad Government. They were not of a pure line but produced very uniform seedlings.

The seeds were sown June 1, 1923 on filter paper. After the roots and plumule had appeared, the seedlings were transferred to liter jars containing Knop's solution; at the appearance of the first nodal roots uniform plants were selected and transferred to the double jars, where every five or six days account was taken of the growth of the plants and of the water and salts absorbed. For convenience and in order to place both root systems under similar conditions, flat-sided jars of equal volume (850 cc.) were used. Placed close together they appeared as one single jar with a double partition in the middle. (Plate 1, Fig. 1 to 3.) To give free access to the root system (for the newly developing nodal roots had to be constantly directed with forceps to the compartment of the double jar assigned to them) the plants were inserted in corks slightly above the level of the partition, as shown in figure 1. The corks were fixed between two croosbeams supported by tin plates fastened to the jars and projecting 1 to 2 cm. above the level. In order to protect the jars from evaporation and to exclude light, paraffined cardboard covers were provided and the jars were wrapped in paper. As there was no possibility of obtaining a sufficient supply of distilled water, the cultures were grown in tap

water. As the water contained much calcium, the following solution gave the best results:

1.0 gm. $NaNO_3$	0.12 gm. KCl
0.25 gm. $MgSO_4$	0.012 gm. $FeCl_3$
0.25 gm. KH_2PO_4	1000 cc. tap water

Nitric acid was added to keep the hydrogen-ion concentration at about pH 6.5 to 6.7, and the solution was changed every 5 to 7 days. The experiments were carried out in a cold greenhouse. The amount of water absorbed was determined by adding water to a constant volume. Changes in the concentration of the culture solutions were determined by the Kohlrausch method. The solutions were restored to their original volume before the concentration was determined. The Kohlrausch method allows one to obtain only approximate values in a solution of several salts. If the changes in dissociation caused by the comparatively insignificant dilution of the solution by the plant are neglected, it may be admitted that the amount of salts absorbed is approximately proportional to the change in specific conductivity.

Records were taken from the time of transfer to the double jars to the time of maturation of the main stem. The plants were harvested after 114 to 116 days of growth.

Experimental data

Development of the plants. Before a survey of the root activity is entered upon, it should be noted that the plants tillered profusely. Simultaneously the nodal roots developed more abundantly than in natural field conditions. The plants possessed from 25 to 50 nodal roots, from 11 to 17 stalks, carrying 7 to 12 heads, although according to the data of other authors and experiment stations, summer crops in field conditions yield from 2 to 4 stalks with 1 to 2 heads and possess about 16 nodal roots [Brenchley (1), Weaver (20), and Percival (8)]. On the other hand the seminal roots of the experimental plants were weakly developed, attaining only a length of 30 to 40 cm., although seminal roots of other species in water cultures have been observed to attain over 100 cm. [Walther (18)], confirmation of which in soil cultures may be found in the literature [Weaver (20), Jackson (3), and Schulze (14)]. In surveying the root activity in the following experiments one must have in view this relation to the development of the root systems and tillers.

The data presented in tables 1 to 4 and in figures 1 to 4, were obtained on duplicate plants from each jar. In tables and curves all the data are calculated to the average activity of one plant in one day in the mentioned interval of time. Data are given, in centimeters, of the average daily increase in growth of the main stem and of the average summary increase of all the tillers measured to the tip end of the highest leaf.

Wheat. Three pairs of plants and one singly planted seedling (four double jars in all) contribute data concerning the root activity of wheat, but for the

sake of brevity the results of only two pairs are presented, the remaining two pairs giving approximately the same results.

Table 1 and figures 1 and 2 show that the absorption of water by the seminal roots rises rapidly at first, reaching its maximum at the time of stalking and energetic tillering, then decreases to about one-half of its maximum and then remains constant, fluctuating only under the influence of weather conditions. Nodal roots gradually increase in their activity beginning with the period of tillering, follow the increased growth of the tillers, finally overtaking the seminal roots at the time of stalking when the activity of the seminal roots falls, reach their maximum at the period of energetic heading and flowering of the tillers, then gradually decrease in their activity accompanying the ripening and desiccation of the older leaves.

In table 2 figures are presented of the total amount of water absorbed by each root system separately in three periods of development: (I) from the stage of 3 leaves to the stage of stalking; (II) from the time of stalking to the time of flowering; and (III) from the time of flowering to the mature stage of the main stem. In the last column is calculated the part taken by the seminal roots in the absorption of water, expressed in per cents of the total amount of water absorbed in the given period.

This table clearly demonstrates that even in the last period of development of wheat the work of the seminal roots does not fall below 17 to 28 per cent. Taking into consideration that the plants possessed from 11 to 17 stalks and 7 to 13 heads, we may calculate that the seminal roots for their part supplied 2 or 3 stalks. Under natural field conditions tillering is far weaker, fewer nodal roots being formed, and the less the tillering and root formation the greater is the relative part played by the seminal roots in the nutrition of the plant, as indicated in table 3.

Absorption of salts by the seminal roots continues throughout the vegetation period of wheat and reaches its maximum near the time of stalking and heading when the main stem attains its maximum increase in growth. The salt absorption by the nodal roots reaches its maximum near the time of the maximum increase in growth of the tillers. Such a coincidence in maximum of growth and of absorption seems to indicate that the seminal roots serve principally the main stem, whereas the nodal roots work for the benefit of the tillers. A second rise in the curve of salt absorption by seminal roots of wheat as well as of barley may be explained either by increased requirements of nutrients during flowering of the main stalk, or more probably, by the growth of "parasite" tillers, which developed on higher nodes of the main stalk. As the nodal roots of these tillers could not reach the water, they had to draw their nutrients through the main stem and thereby stimulated the activity of the seminal roots.

That the nodal roots absorbed a more dilute solution than the seminal ones, is shown in columns 11 and 12, table 1.

Barley gave a similar picture of root activity (table 4 and fig. 3 and 4) with the only difference that the seminal roots did not reveal a decrease in water

TABLE 1

Water and salt absorption, growth and development of wheat no. 5

DATE	NUMBER OF DAYS	AVERAGE DAILY ABSORPTION OF WATER				AVERAGE DAILY ABSORPTION OF SALTS				AMOUNT OF WATER ABSORBED PER MILLIGRAM OF SALT		DEVELOPMENT AND GROWTH IN HEIGHT							
													Main stem			Tillers			
		By the seminal roots	By the nodal roots	Total	Nodal root absorption per unit of seminal root absorption	By the seminal roots	By the nodal roots	Total	Nodal root absorption per unit of seminal root absorption	By the seminal roots	By the nodal roots	Date	Stage of development	Height to the tip end of the leaf	Average daily increase in height	Number of tillers	Summary height of all tillers to end of leaf	Daily increase in height	Number of heads
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		cc.	*cc.*	*cc.*		*mgm.*	*mgm.*	*mgm.*						*cm.*	*cm.*		*cm.*	*cm.*	
June 23–25	2	2.12	....	2.1	0	..	..	..	....	....	....	June 22	3 leaves						
June 25–27	2	3.15	....	3.2	0	..	..	..	....	....	....								
June 28–30	2	3.80	0.9	4.7	0.24	..	..	..	....	....	....	June 28	Tillering	30.75		1.0	9.5	0.3	
June 30 to July 3	3	8.66	1.5	10.2	0.17	..	..	..	....	....	....	June 30	4 leaves		1.7	1.5	10.0		
July 3–8	5	17.65	3.5	21.2	0.19	21	7	28	0.33	0.84	0.49	July 3	5 leaves	38.50		1.5		4.9	
July 8–11	3	19.16	6.9	26.1	0.35	..	..	..	....	....	....				1.0				
July 11–13	2	28.00	17.9	45.9	0.63	..	..	..	....	....	....	July 10		45.00		3.0	59.5		
July 13–18	5	19.60	16.3	35.9	0.83	26	14	4.0	0.52	0.75	1.17	July 15	Stalking	54.00	1.8	3.0	76.0	3.3	
July 18–21	3	8.08	9.4	17.5	1.16	..	..	..	....						1.3			5.3	
July 21–25	4	10.06	13.0	23.1	1.29	..	..	..	....			July 20		61.50		4.5	102.5		
July 25–30	5	11.30	18.4	29.7	1.63	20	24	44	1.20	0.57	0.77	July 25		66.00	0.9	5.5	132.5	6.0	
July 30 to August 3	4	4.37	10.8	15.2	2.47	..	..	..	....				Heading		0			10.0	
August 3–6	3	6.16	17.2	23.4	2.79	..	..	..	....			August 3	Flowering	67.00		8.5	242.5		1.0
August 6–11	5	9.70	24.2	33.9	2.49	11	26	37	2.30	0.88	0.93				0			10.9	
August 11–14	3	6.66	18.2	24.9	2.57	..	..	..	....			August 11		67.00		8.5	329.0		2.5
August 14–17	3	9.00	26.8	35.8	2.98	..	..	..	....									12.0	
August 17–23	6	9.00	26.8	35.8	2.98	17	30	47	1.7	0.53	0.89	August 19				9.0	425.0		3.5
August 23–26	3	11.08	27.2	38.3	2.45	..	..	..	....									10.2	
August 26–29	3	12.50	31.7	44.2	2.53	..	..	..	....			August 27				9.5	507.0		6.5
August 29 to September 3	5	9.37	25.2	34.6	2.66	16	31	47	1.9	0.58	0.81							3.8	
September 3–10	7	5.71	13.5	19.2	2.37	..	..	..	....			September 6				11.5			
September 10–15	5	8.25	18.9	27.2	2.28	16	20	36	1.3	0.52	0.94								
September 15–21	6	12.70	33.0	45.7	2.59	..	..					September 21				11.5	603.0		7.0

absorption after stalking of the main stem. On the whole the seminal roots of barley are slightly more active than those of wheat and play a greater part in the provision of water, supplying from 29 to 31 per cent of the total amount of water absorbed by the plant. This may probably be explained by the healthier growth of barley in its first stages of development when the seminal root system is formed. The wheat at that time was weaker and suffered from chlorosis.

It is interesting to compare the absorption of water by the different root

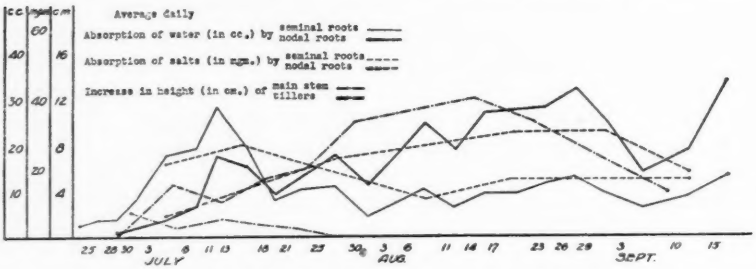

Average daily
Absorption of water (in cc.) by seminal roots / nodal roots
Absorption of salts (in mgm.) by seminal roots / nodal roots
Increase in height (in cm.) of main stem / tillers
JULY
AUG.
SEPT.

FIG. 1. WATER AND SALT ABSORPTION, AND GROWTH OF WHEAT NO. 5

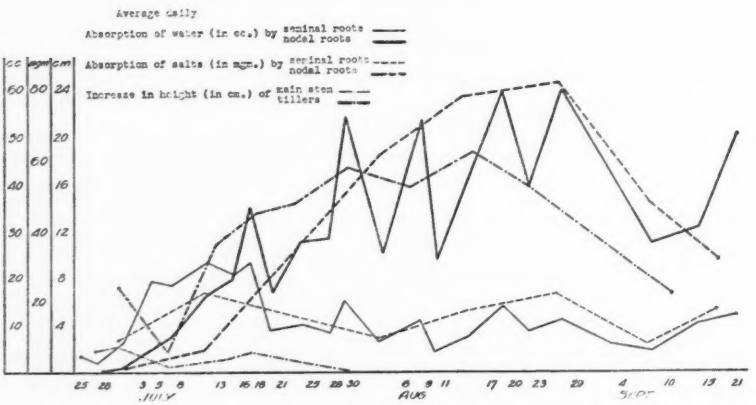

Average daily
Absorption of water (in cc.) by seminal roots / nodal roots
Absorption of salts (in mgm.) by seminal roots / nodal roots
Increase in height (in cm.) of main stem / tillers
JULY
AUG
SEPT.

FIG. 2. WATER AND SALT ABSORPTION, AND GROWTH OF WHEAT NO. 6

systems of wheat and barley calculated in relation to 1 gm. of dry weight of the roots. Very often in determinations of root activity in different soil layers, the dry weight of the roots found in these layers serves as a measure. Table 5 shows that the seminal roots in the third period of growth absorb almost double the amount of water absorbed by the nodal roots per unit of dry weight.

From the results of this series of experiments one can conclude that in water cultures the investigated species of wheat and barley with a comparatively

weak seminal root system and profuse tillering accompanied by the formation of a rich nodal root system, *maintain the vitality and activity of the seminal roots up to the time of harvest.* These roots continue to function in the last periods of vegetation, supplying, in the conditions mentioned above, 20 to 25 per cent of the water and salts necessary for the plant.

TABLE 2

Total amount of water absorbed by each root system of wheat separately in three periods of development

PERIODS	NUMBER 5*			NUMBER 6*		
	Absorption of water.		Activity of seminal roots	Absorption of water		Activity of seminal roots
	Seminal roots	Nodal roots		Seminal roots	Nodal roots	
	cc.	*cc.*	*per cent*			*per cent*
I. June 23 to July 18	687.8	324.1	68	742.8	506.9	59
II. July 18 to August 3	277.0	431.3	39	308.7	879.4	26
III. August 3 to September 21	888.2	2287.6	28	878.0	4087.8	17
Total	1853.0	3043.0	38	1929.5	5474.1	26
	NUMBER 9*			NUMBER 10†		
	August 26 to September 21			August 10 to September 21		
	cc.	*cc.*	*per cent*	*cc.*	*cc.*	*per cent*
From heading to maturation	1103	3321	25	643	1660	28

* Two plants.

† One plant.

TABLE 3

Relative activity of seminal roots of wheat with different numbers of tillers and nodal roots

NUMBER OF JARS	NUMBER OF TILLERS	NUMBER OF NODAL ROOTS	NUMBER OF HEADS	ACTIVITY OF SEMINAL ROOTS
				per cent
5	11.5	23	7.0	28
10	17.0	..	8.0	24
9	14.0	18	10.0	23
6	14.5	48	12.5	18

The correlation between root activity and increase in growth of the main stem and tillers leads to the supposition that the seminal roots nourish principally the main stem, whereas the nodal roots work more for the tillers.

Experiments with summer rye were not completed because of the unexpected affection of rye by chlorosis at the period of flowering. The first half of these experiments, however, demonstrates the vitality of the seminal roots at least to the time of flowering. This summer rye resembled most summer field crops in that it had one or two tillers and five to ten nodal roots. As may be seen in table 6 their seminal roots performed over half of the work.

TABLE 4

Water and salt absorption, growth and development of barley no. 7

DATE	NUMBER OF DAYS	AVERAGE DAILY ABSORPTION OF WATER				AVERAGE DAILY ABSORPTION OF SALTS				AMOUNT OF WATER ABSORBED PER MILLIGRAM OF SALT		DEVELOPMENT AND GROWTH IN HEIGHT							
													Main stem			Tillers			
		By the seminal roots	By the nodal roots	Total	Nodal root absorption per unit of seminal root absorption	By the seminal roots	By the nodal roots	Total	Nodal root absorption per unit of seminal root absorption	By the seminal roots	By the nodal roots	Date	Stage of development	Height to tip end of the leaf	Average daily increase in height	Number of tillers	Summary height of all tillers to end of leaf	Daily increase in height	Number of heads
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		cc.	*cc.*	*cc.*		*mgm.*	*mgm.*	*mgm.*						*cm.*	*cm.*		*cm.*	*cm.*	
June 25–30	5	3.1	0.5	3.6	0.16	..	..	..	....	....	....	June 28	3 leaves	32.0					
June 30 to July 3	3	7.7	1.0	8.7	0.13	..	..	..	....	....	....				2.1				
July 3–8	5	14.2	3.2	17.4	0.22	24	6	30	0.25	0.59	0.54	July 3	4 leaves	42.5		0.5	4.5		
July 8–11	3	17.3	4.7	22.0	0.27	..	..	..	....	....	....		Tillering		0.6			2.1	
July 11–13	2	26.1	12.8	38.9	0.49	..	..	..	....	....	....	July 10		46.0		1.0	19.5		
July 13–18	5	23.5	15.6	39.1	0.66	29	25	54	0.86	0.81	0.62	July 15	Stalking	49.5	0.9	2.0	55.0	7.1	
July 18–25	7	15.4	18.1	33.5	1.17	35	40	75	1.14	0.44	0.45	July 20		60.0	2.1	3.5	115.0	12.0	
July 25–28	3	17.6	29.3	46.9	1.67	..	..	..	....	....	....	July 25		71.0	2.2	4.0	173.0	11.6	
July 28–30	2	26.5	63.7	90.2	2.40	..	..	..	....	....	....				0.6			11.4	
July 30 to August 6	7	14.1	42.2	56.3	2.99	28	88	116	3.14	0.50	0.48	August 3		76.5		7.0	277.0	13.2	
August 6–9	3	22.0	73.4	95.4	3.33	..	..	..	....	....	....				1.3				
August 9–11	2	14.7	46.7	61.4	3.17	..	..	..	....	....	....								
August 11–17	6	14.8	60.5	75.3	4.09	25	74	99	2.96	0.59	0.80	August 11	Heading	87.0	0	8.0	483.0	14.7	
August 17–20	3	22.2	87.3	109.5	3.93	..	..	..	....	....	....								
August 20–23	3	16.1	62.3	88.4	3.87	..	..	..	....	....	....	August 19	Flowering	87.5	0	8.5	601.0	20.7	2.5
August 23–29	6	26.2	82.4	108.6	3.14	39	60	99	1.54	0.67	1.37	August 27		87.5		11.0	766.0		2.5
August 29 to September 4	6	16.6	52.8	69.4	3.18	..	..	..										7.7	
September 4–10	6	12.3	34.4	48.7	2.79	39	57	96	1.46	0.31	0.60	September 6		....		12.5			6.0
September 10–15	5	12.9	35.0	47.9	2.71	..	..	..											
September 15–21	6	14.8	56.3	71.1	3.80	29	48	77	1.65	0.51	1.17	September 21		....		12.5	958.0		6.5

EXPERIMENTS WITH THE REMOVAL OF ONE OF THE ROOT SYSTEMS

Methods

When the results of the first series of experiments are studied the objection might arise that because the seminal roots are active in water, this does not mean that they remain active in the soil where they may be unable to surmount less favourable conditions. Although the activity of seminal roots under soil

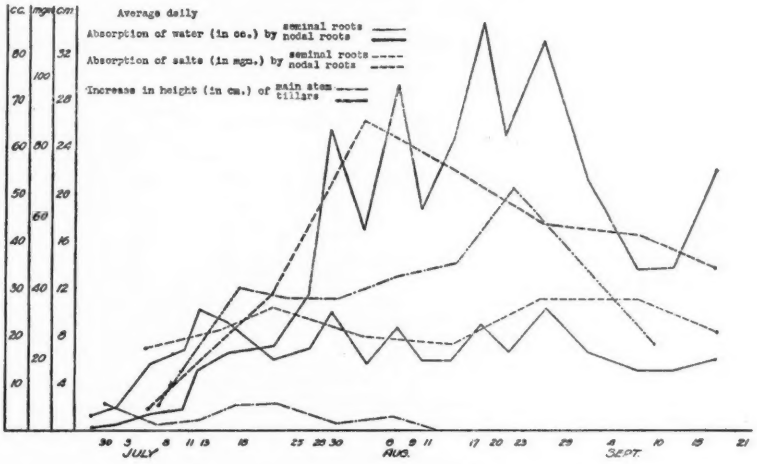


FIG. 3. WATER AND SALT ABSORPTION, AND GROWTH OF BARLEY NO. 7

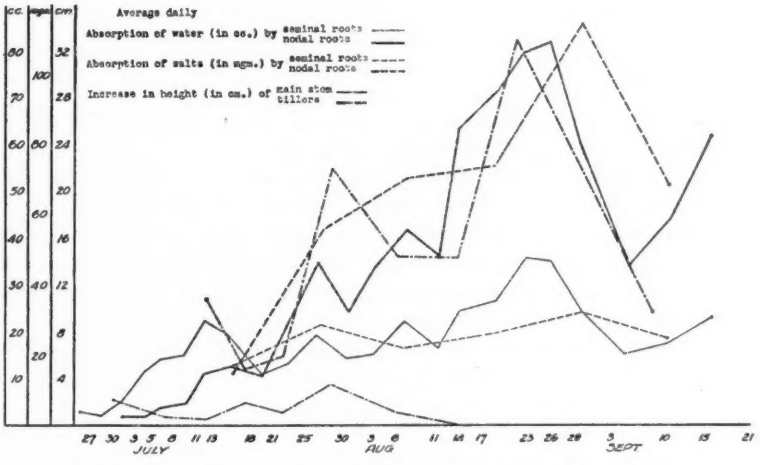


FIG. 4. WATER AND SALT ABSORPTION, AND GROWTH OF BARLEY NO. 8

conditions cannot be proved directly with the aid of water cultures, nevertheless indirectly their necessity may be demonstrated after the formation of the nodal root system. If at the time mentioned, the seminal root system be removed and this removal should perceptibly affect the plant or some part of it that develops normally in natural conditions, it may be concluded: first that these roots are necessary for the normal development of the plant; and secondly, that certain of the organs are more dependent on the given root system. It also seemed of interest to study the vitality and energy of both root systems; that

TABLE 5

Absorption of water by seminal and nodal root systems of wheat and barley in relation to dry weight of roots

PLANT AND NUMBER OF JAR	DRY WEIGHT OF ROOTS		AVERAGE DAILY ABSORPTION OF ROOTS PER GRAM OF DRY WEIGHT	
	Seminal	Nodal	Seminal	Nodal
	gm.	*gm.*	*cc.*	*cc.*
Wheat number 5	0.169	0.709	107	65
Wheat number 6	0.136	0.947	131	88
Barley number 8	0.135	0.650	326	173

TABLE 6

Activity of seminal roots in summer rye

PERIODS	NUMBER OF DAYS	NUMBER 1*			NUMBER 2*		
		Water absorbed		Activity of seminal roots	Water absorbed		Activity of seminal roots
		Seminal roots	Nodal roots		Seminal roots	Nodal roots	
				per cent			*per cent*
I. June 19 to July 3	14	90.6	42.3	68	48.7	11.3	81
II. July 3 to July 30	25	426.3	358.3	54	682.7	327.8	67

* Two plants.

is, how far they can substitute each other and whether the crop plant can accomplish its development with seminal roots only.

In this series 28 barley seedlings were transferred to 750-cc. bottles. Of these plants 7 served as controls (series I). From 6 of these plants the newly developing nodal roots were constantly removed (series II). From 5 other plants the seminal roots were removed after the beginning of stalking, when they possessed a developed nodal root system consisting of 10 to 17 roots and when their activity was overtaking that of the seminal ones, judging by the cultures with isolated root systems (series III). Recording methods were the same as in the preceding series of experiments.

Experimental data

Development and root activity of series I, II, and III: The main stem of the barley plants of series II developed normally as in the controls, ripening even

slightly sooner, but tillering very soon ceased, and only two or three tillers developed showing slight affection by chlorosis. In series III, where the seminal roots were removed, on the contrary, the main stem was affected most—it suffered from chlorosis and fell back in growth from the tillers. Though in each series the tillers were taller than the main stem, this difference between the main stem and the tallest tiller in the second series, averaged only 1.4 cm., 18 cm. in the controls, and 28 cm. in series III. The absence of nodal roots affected the quantity more than the quality of tillers. The absence of seminal roots affected the quality of the main stem, notwithstanding the vigorous development of the tillers. This fact again confirms the supposition that the seminal roots are necessary for the development of the main stem, whereas the nodal roots nourish the tillers. It is also interesting to note, that whereas the removal of the nodal roots hastened the process of ripening, the absence of the seminal roots retarded it.

The readings of salt absorption show that whereas in series II a maximum of salt absorption is reached at the time of stalking of the main stem, in series III this maximum is retarded to the time of stalking of the tillers. (Table 7.)

Concerning water absorption—the roots of series III did not eventually overtake the controls—the seminal roots of the controls seemed to supply an additional quantity of water up to the time of ripening. (Table 7.)

To a certain extent both root systems seemed to accommodate themselves to the new conditions, for their summary activity exceeded the activity of the controls. On the whole one may assert that both root systems are not capable of entirely replacing each other; for the harmonious development of summer crops both root systems are necessary.

Data of the yield. The total yields of plants in the different series were obtained in the order anticipated: series I yielded the largest total green or dry weight, then followed series III, and last series II. The relative development of different parts of the plant in connection with the presence of one or the other root system presented greater interest, for it proved that both systems are necessary to the plant in its last stages of growth.

Measurements of the size of the head and of the dry weight of the head or grain of the main stem (table 8) are higher in the series possessing seminal roots, and even greater in the second series, possessing seminal roots only, than in the first control series having both root systems. This may probably be explained by the phenomenon that the absence of the nodal roots stimulated the development of the seminal ones (table 9), which nourish the main stem.

The removal of seminal roots not only checked the growth of the main stem, but affected also the succeeding stages of the head and grain development as is shown in table 9. All this seems to prove that the seminal roots are necessary for the development of the main stem, and hence are active in the soil.

Table 9 shows that the removal of the nodal roots reduces the weight of the stems, whereas the yield of the ripe grain is decreased but slightly. On the

TABLE 7

Water absorption, salt absorption, growth and development of barley in the experiment series with removal of roots

I—control; II—nodal roots removed constantly; III—seminal roots removed. (All figures averages calculated to 1 plant.)

DATE	AVERAGE DAILY WATER ABSORPTION			AVERAGE DAILY SALT ABSORPTION			DATE	AVERAGE DAILY INCREASE IN HEIGHT OF THE MAIN STEM			TILLERS						NUMBER OF HEADS		
											Number of tillers			Increase in height of all tillers					
	I	II	III	I	II	III		I	II	III	I	II	III	I	II	III	I	II	III
	cc.	*cc.*	*cc.*	*mgm.*	*mgm.*	*mgm.*		*cm.*	*cm.*	*cm.*				*cm.*	*cm.*	*cm.*			
June 25–29	1.6	1.7	.....*	....	....	....	June 24	0.1	0.5	..	0.7	1.0	...	1.3	2.1	..			
June 29 to July 1	4.4	4.2	.....	12.2	10.7	....	June 29	2.5	1.8	...	1.6	1.8	...	5.1	5.4				
July 1–4	10.3	9.3	.....				July 4	1.2	1.2		2.0	2.0	...	5.6	4.5				
July 4–6	17.3	12.3	.....	12.5	....	....	July 9	1.8	1.2	0.6	2.5	2.0	2.6	8.8	1.9	3.9			
July 6–9	26.6	22.8	.....				July 15	2.2	1.2	0.7	3.3	2.1	3.0	12.3	3.4	8.5			
Removal of seminal roots in series III							July 20	1.8	1.3	2.0	4.3	2.1	3.2	20.3	4.9	13.8			
July 9–11	43.3	34.3	33.1	48.7	31.3	24.6	July 26	0.5	0.2	0.2	5.7	2.6	4.6				1.0	0.8	0.8
July 11–14	70.3	49.5	54.2				July 31							10.4	1.5	8.6			
July 14–16	55.3	39.1	44.3	46.1	25.0	37.8	August 1–5	0	0	0	5.8	2.5	5.0	6.7	0.3	9.8	2.4	2.3	1.6
July 16–19	76.4	47.6	56.9				August 8				8.0	3.0	6.2	18.8	2.0	11.4	3.8	2.8	3.4
July 19–21	37.9	23.0	34.5	45.6	28.4	41.9	August 15				9.6	2.7	6.8	17.8	1.6	12.3	5.1	3.1	3.8
July 21–26	72.3	41.1	55.2				August 22				10.8	3.0	8.6				5.8	3.1	4.8
July 26–29	87.5	43.8	65.1	51.6	27.7	44.9	August 29				10.8	2.8	8.6	5.9	1.6	4.8	6.7	3.1	5.4
July 29 to August 1	96.6	53.7	76.6				September 6										7.0	3.3	6.0
August 1–5	73.0	36.8	57.1	46.0	24.5	43.7	September 17				11.0	3.1	8.6				7.0	3.3	6.2
August 5–9	107.3	40.2	79.0				September 20												
August 9–12	65.4	28.2	50.9	....	....	....													
August 12–15	143.7	52.2	112.6	....	....	....													
August 15–18	58.3	19.3	47.8	52.8	21.4	59.0													
August 18–21	145.6	54.1	118.1																
August 21–24	132.7	41.9	106.5	....	....	....													
August 24–27	131.9	34.5	112.3	....	....	....													
August 27 to September 3	118.7	26.6	94.8	38.1	16.5	50.9													
September 3–8	74.5	14.1	56.5	....	....	....													
September 8–13	43.7	9.0	36.7	....	....	....													
September 13–17	96.3	15.5	76.9	....	....	....													
September 17–20	65.0	10.3	52.7	....	....	....													

* Before the removal of the seminal roots series III was combined with series I.

other hand, the removal of the seminal roots affects largely the yield of the ripe grain. In connection with the retarding influence of the absence of seminal roots upon the process of ripening, and the vigorous tillering, caused by the vigorous nodal root system, series III possesses a fair supply of unripe grain.

TABLE 8

Yield of tops, dry weight, and length of head of the main stem, and dry weight of tillers

(Average for each plant)

NUMBER OF SERIES	MAIN STEM				TILLERS			
	Dry weight			Length of head	Dry weight			
	Straw	Heads	Grain		Straw	Heads	Mature grain	Green grain
	gm.	*gm.*	*gm.*	*cm.*	*gm.*	*gm.*	*gm.*	*gm.*
I	0.886	1.466	1.256	8.07	7.88	6.659	2.43	2.333
II	0.894	1.585	1.335	7.66	1.94	2.704	1.19	0.915
III	0.813	1.024	0.812	7.20	6.04	4.635	0.30	2.790
IV	0.915	1.543	1.280	8.00	1.58	2.068	0.91	0.993

TABLE 9

Yield of roots and absorption of water, during the last month, per gram of dry roots

(Average calculated to 1 plant, in cubic centimeters)

NUMBER OF SERIES	NUMBER		LENGTH		DRY WEIGHT		DAILY WATER ABSORPTION PER GRAM OF DRY ROOTS	
	Seminal roots	Nodal roots	Seminal roots	Nodal roots	Seminal roots	Nodal roots	Seminal roots	Nodal roots
			cm.	*cm.*	*gm.*	*gm.*		
I	8.1	37.6	30.5	28.6	0.101	0.490*	152	
II	8.8	....	40.8	....	0.146	.....	137	..
III	...	41.8	....	29.0	.....	0.690	...	76
IV†	8.6	....	41.2	....	0.110	.....	150	..

* Some of the roots were badly torn and lost in the process of disentangling the seminal and nodal roots. This may partly explain the high figure of absorption per unit of dry weight in series I.

† Series IV, not mentioned in the text, consisted of only 3 plants, the nodal roots of which were not cut from the beginning of their development, but all simultaneously, 2 days after the removal of the seminal roots in series III. They thus had less time to adapt the development of their seminal root system, which is obvious from the data concerning their weight and the weight of the tillers as compared with series II.

As in the experiments with isolated root systems, the seminal roots absorb more water per unit of dry weight, than do the nodal ones (table 8). The latter may be of practical interest in solving the question: From what layers do the crop plants absorb water and minerals? Not only must the relative weight of roots at different depths be known, but also the energy of absorption per

unit of this dry weight. Most of the authors indicate that the main part of roots of grassy crop plants is distributed to the depth of 25 to 30 cm. Judging, however, by the illustrations of Schulze (13), Rotmistrov (12), and Weaver, Jean and Crist (20), the seminal roots grow more or less vertically into the depths of the soil; their weight is insignificant, but when their greater activity per unit of dry weight is taken into consideration[2] absorption from the deeper soil layers will prove greater than is generally accepted, and no doubt the seminal roots play a greater rôle in plant nutrition than as yet has been assigned to them. This may be the case particularly in conditions where the crops develop not more than one or two tillers and in consequence few nodal roots.

The aim of this work was to investigate whether the seminal roots continue to function after the formation of the nodal root system and, further, to examine the rôle of the former in the supplying of water and nutrients and how far they may guarantee the crop in the case of inhibition of nodal root formation. Insofar as concerns barley, wheat, and rye in water cultures, the answer is positive.

Experiments of Wiggans (21), Walworth and Smith (17), and Sieglinger (15) have shown that not only different kinds, but also different varieties of the same crop plants do not possess the same number of seminal roots. Observations of wheat in water cultures (19) have also shown that seminal roots may attain lengths from 40 to 110 cm. Obviously in the case of the appearance of conditions unfavorable for the development of nodal roots, the advantages will be on the side of the varieties possessing a more vigorous seminal root system. Before drawing any conclusions, however, it is essential to verify the activity of seminal roots in soil cultures.

The above mentioned experiments were carried out in the summer of 1923. In the summer of 1924 the second series of experiments was repeated, with modifications, in soil cultures with summer barley. The results more or less confirm those obtained in water cultures, but as the data have not been compiled, more detailed results of the soil experiments will form the subject of another paper.

SUMMARY

1. Experiments were carried out with summer wheat, barley, and rye in water cultures with isolated nutrition of seminal and nodal roots.

2. Records of water and salt absorption have shown that the seminal roots are active up to the time of harvest and supply two or three stems of the plant with nutrients.

3. The correlation between the time of maximum activity of the seminal

[2] Probably the same activity may be assigned to the ends of the nodal roots in the greater depths where they acquire the slenderness of seminal roots, whereas the upper part of the nodal roots forming the heavy bulk does not take part in the absorption.

roots and the maximum growth of the main stem as well as between the time of the maximum activity of the nodal roots and the maximum growth of the tillers seems to prove that the seminal roots supply principally the main stem; the nodal roots, the tillers.

4. The decrease in activity (amount of water absorbed) caused by the removal of either the nodal or the seminal root system is never entirely completed during the whole vegetative period by the remaining root systems.

5. The removal of the seminal roots in the period of stalking suppresses the development of the main stem and lengthens the period of vegetation: this evokes the supposition that the seminal roots are indispensable for the normal development of the crop plant and are consequently active in the soil.

6. The removal of the nodal roots checks tillering, hastens maturing, does not affect the quality of the grain of the main stem, nor even that of the first tiller.

7. These last two points confirm the conclusion drawn from the first series of experiments that the seminal roots serve the main stem, whereas the nodal roots serve the tillers.

8. Whereas the removal of the seminal roots decreases the yield of grain, the removal of the nodal roots decreases principally the yield of straw.

9. The removal of the nodal roots stimulates the growth and activity of the seminal roots.

10. The seminal roots absorb almost double the amount of water per unit of dry weight in comparison to the nodal roots.[3]

REFERENCES

(1) BRENCHLEY, W., AND JACKSON, V. 1921 Root development in barley and wheat under different conditions of growth. *In* Ann. Bot. (London), v. 35, p. 533–556.
(2) FRUWIRTH, E. 1921 Der Getreidebau. Max Jänecke, Leipzig.
(3) JACKSON, V. 1922 Anatomical structure of the roots of barley. *In* Ann. Bot. (London), v. 36, p. 21–39.
(4) KIRCHNER, O., LOEW, E., AND SCHRÖTER, C. 1908 Lebensgeschichte der Blütenpflanzen Mitteleuropas. *In* Stuttgart. Lief. 8, v. I, Abt. 2, p. 41.
(5) MILLER, E. C. 1916 Comparative study of the root systems and leaf areas of corn and the sorghums. *In* Jour. Agr. Res., v. 6, p. 311–331.
(6) MONTGOMERY, E. G. 1913 The Corn Crops. Macmillan, New York.
(7) NOWACKI, A. 1920 Anleitung zum Getreidebau. Paul Parey, Berlin.
(8) PERCIVAL, JOHN 1921 The Wheat Plant. Duckworth and Co., London.
(9) PRIANISCHNIKOV, D. N. 1922 Crop Plants, Part I. Moscow.
(10) QUANTE, HUGO 1913 Die Gerste, ihre botanischen and brautechnischen Eigenschaften und ihre Anbau. Paul Parey, Berlin.
(11) ROBBINS, WILFRED W. 1917 The Botany of Crop Plants. Blakiston, Philadelphia.

[3] After this work had been accomplished and written, the work of L. F. Locke and J. Allen appeared in the April 1924 number of the Journal of the American Society of Agronomy, only recently obtained in Leningrad. The authors mention two observations, made in field conditions, confirming the possibility of wheat plants developing to maturity supported by the seminal roots only, when weather conditions do not allow the development of the coronal or permanent root system.

(12) ROTMISTROV, V. 1907 The extension of the roots of summer crop plants. *In* Zhur. Opytn. Agron. (Russian), 1907, v. 8, p. 667–705; 1908, v. 9, p. 1–24.

(13) SCHINDLER, FRANZ 1920 Handbuch des Getreidebaues. Paul Parey, Berlin.

(14) SCHULZE, B. 1911 Wurzelatlas. Berlin. (*quoted by* Franz Schindler, 1920, Handbuch des Getreidebaues.)

(15) SIEGLINGER, B. JOHN 1920 Temporary roots of the sorghums. *In* Jour. Amer. Soc. Agron., v. 12, p. 143–145.

(16) SLESKIN, P. R. 1897 An attempt to survey our knowledge concerning the biology of our crop plants. Selskoje Chosiastwo i Lesovodstwo, v. 184, no. 2 and 3, p. 355 and 611.

(17) WALWORTH, E. H., AND SMITH, L. H. 1918 Variations in the development of secondary rootlets in cereals. *In* Jour. Amer. Soc. Agron., v. 10, p. 32–35.

(18) WALTHER, O. A. 1917 Influence of the actual reaction of the medium upon the development, yield and transpiration of beloturka wheat in water cultures. (Unpublished.) *Delivered before the* Russian Botanical Society.

(19) WALTHER, O. A., AND KRASSOVSKY, I. V. 1924 The influence of the reaction of the medium upon the development and anatomical structure of the roots of wheat. (Unpublished.) *Delivered before the* Russian Botanical Society.

(20) WEAVER, J., JEAN, FR., CRIST, J. 1922 Development and activities of roots of crop plants. Carnegie Inst. Washington Pub. 316.

(21) WIGGANS, ROY C. 1916 The number of temporary roots in cereals. *In* Jour. Amer. Soc. Agron., v. 8, p. 31–37.

(22) WILLIAMS, V. R. 1922 General Agriculture. Moscow.

(23) ZAWODNY, J. 1898 Beitrag zur Kenntnis der Wurzel von Sorghum Saccharatum. *In* Ztschr. Naturw., v. 70, p. 169–188.

PLATE 1

FIGS. 1, 2, 3. DIAGRAM OF JARS USED IN ROOT STUDIES

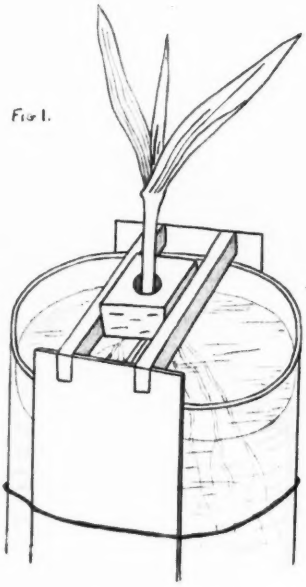


Fig. 1.

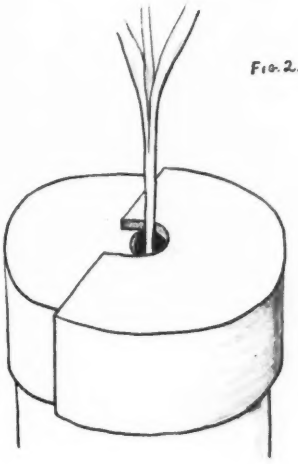


Fig. 2.

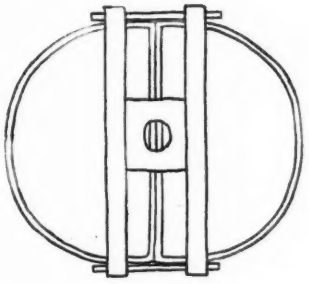
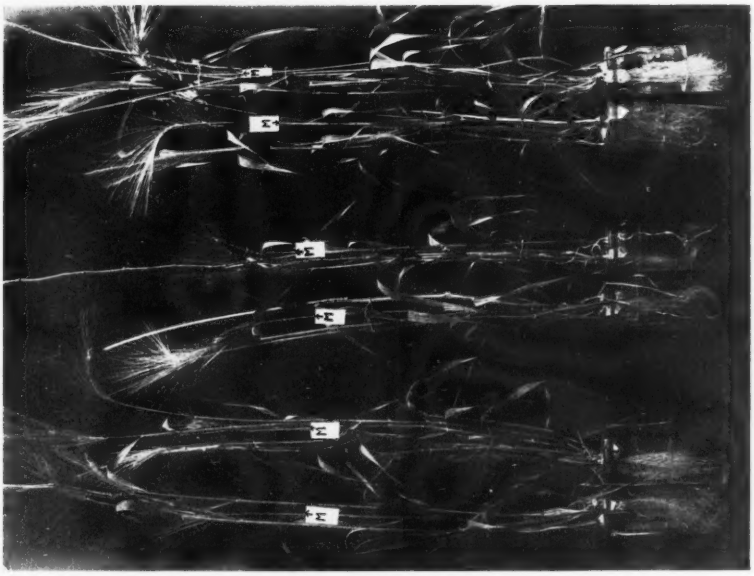
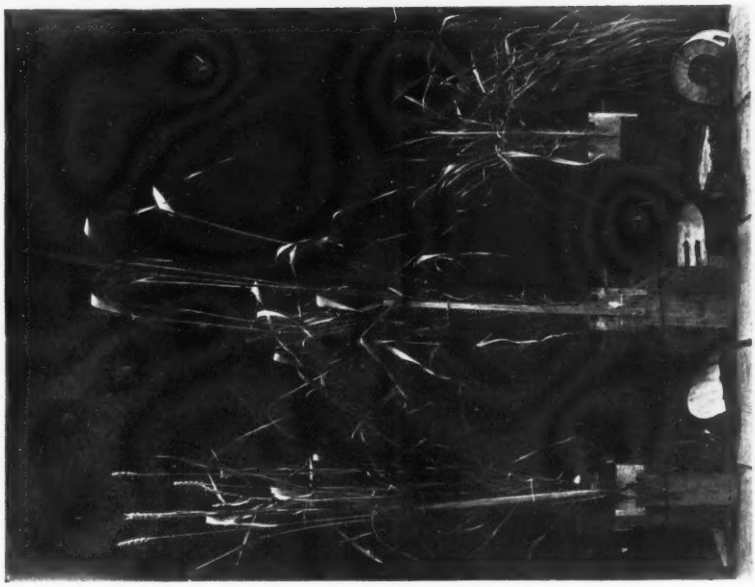


Fig. 3.

PLATE 2

(Photographed August 15, at time of flowering)

Left, experiments with isolated root systems. From left to right: Wheat No. 6; Barley No. 8; and winter rye (not mentioned in the text).

Right, experiments with the removal of one of the root systems. The main stalk is marked "M." From left to right: Series III—seminal roots removed; series II—nodal roots removed; series I—control.

(Note character of root system and relative amount of water absorption for the same period of time.)